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Introducing Driverless Cars to UK Roads

WORK PACKAGE 5.3

Deliverable D11

Understanding interactions between autonomous vehicles and other road users

A Literature Review

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June 2016

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Summary

This review draws on literature relating to the interactions of vehicles with other vehicles, interactions between vehicles and infrastructure, and interactions between autonomous vehicles and cyclists and autonomous vehicles and pedestrians. The available literature relating to autonomous vehicles interactions is currently limited and hence the review has considered issues which will be relevant to autonomous vehicles from reading and evaluating a broader but still relevant literature.

The project is concerned primarily with autonomous vehicles within the urban environment and hence the greatest consideration has been given to interactions on typical urban roads, with specific consideration also being given to shared space. The central questions in relation to autonomous vehicles and other road users revolve around gap acceptance, overtaking behaviour, behaviour at road narrowings, the ability to detect and avoid cyclists taking paths through a junction which conflict with the autonomous vehicle's path, and the ability of autonomous vehicles to sense and respond to human gestures. A long list of potential research questions has been developed, many of which are not realistically answerable by the Venturer project. However, the following list summarises the important research questions which might potentially be answered by the current project. These are offered as the basis for the more detailed consideration of the conduct of the interaction trials.

1. Do approaching AVs, when they are clearly distinguishable as such, engender a different gap acceptance behaviour amongst other road users, at priority junctions?
2. Do approaching AVs, when they are clearly distinguishable as such, engender a different gap acceptance behaviour amongst other road users, at roundabouts?
3. How will AVs behave in shared space?
4. What is the extent to which an AV, when not being driven, can remain what might be termed 'passively' safe by preventing passenger egress when it is not safe for the occupants or others in the vicinity, such as cyclists to do so?
5. Are AVs able to overtake cyclists both with and without centre line markings with no difference in the impact on cycle users perceptions of safety?
6. For different speeds, what is an appropriate distance to be provided by an AV when overtaking a cyclist in order to provide a minimum level of comfort for the cyclist?
7. How will cycle users negotiate road narrowings with AVs without the facility to use eye contact as part of negotiating the manoeuvre?
8. How accurate are AVs in detecting cyclists who are making straight on manoeuvres at junctions across side roads either within the carriageway or on adjacent cycle tracks and what is the ability of the AV to come to a correct decision about its behaviour in relation to the cyclist or cyclists?
9. What is the extent to which AVs are able to decipher cyclists arm signals accurately at junctions?
10. What roles will cyclists and pedestrians have in a driverless society and how will the presence of driverless vehicles change pedestrians' and cyclists' facility preferences and behaviour?
11. How will AV sensing be able to detect and react to signals that pedestrians are gesturing and how will these be interpreted by the AV in its decision making?
12. Will pedestrians adjust the gap that they are prepared to accept to make a crossing of a road when the next approaching vehicle is demonstrably an AV rather than a human-driven vehicle?
13. Will pedestrians' intention to cross change as the approaching vehicle is demonstrably an AV?
14. Are AVs programmable to effectively and automatically adapt their speed within zebra crossing 'decision zones' regardless of whether pedestrians are present?
15. How good are AVs at detecting pedestrians approaching and crossing side roads and are they able to respond accordingly?
16. How do pedestrians react to a vehicle which is demonstrably autonomous when deciding whether to start to cross a side road?

17. How does the general population think AVs ought to be programmed to take action in the event of unavoidable collisions involving pedestrians?

1 Introduction

It appears relatively certain that the coming decades will witness a progressive transfer from the current predominance of human-controlled motorised vehicles to vehicles with increasing degrees of autonomy. It is less certain, however, how such Autonomous Vehicles (AVs) will integrate into the full range of existing types of public rights of way, and, more importantly, how they will integrate with the full range of road users, including pedestrians, cyclists and drivers and passengers of non-autonomous motor vehicles.

This literature review is the third review providing background to the VENTURER work package concerned with acceptability. The first review considered market opportunities and expectations, the second literature review considered user acceptance and response, particularly in terms of the process of return of control from autonomy to the driver. This third review considers the interactions of autonomous vehicles with other road users on the public road.

The review is introduced by a summary of types of autonomous vehicles. It then goes on to discuss the different scenarios in which autonomous vehicles may be used. This is followed by a section which provides an introductory discussion on collisions, conflicts and interactions.

The remaining sections in the review deal with vehicle-to-vehicle and vehicle-with-infrastructure interactions (Section 2), vehicle-with-bicycle interactions (Section 3) and finally vehicle-with-pedestrian interactions (Section 4). The emerging research questions are summarised in the concluding section (Section 5).

In drafting this literature review, we have drawn on literature from around the world. We have pointed out where some of the behaviours reported may not accord with UK observations. This breadth of literature has been included, however, in order to ensure that the full range of possible interactions that may result as a consequence of the introduction of AVs onto the UK's roads may be more fully understood and properly contextualised.

1.1 The nature of autonomous vehicles

Levels of autonomy are fully discussed in the literature review¹ considering market opportunities. Generally accepted levels of autonomy are derived from the United States of America's National Highway Traffic Safety Administration preliminary statement of policy concerning automated vehicles (NHTSA 2013) and are summarised for reference purposes as follows:

- Level 0: The driver completely controls the vehicle at all times.
- Level 1: Individual vehicle controls are automated, such as electronic stability control or automatic braking.
- Level 2: At least two controls can be automated in unison, such as adaptive cruise control in combination with lane keeping.
- Level 3: The driver can fully cede control of all safety-critical functions in certain conditions. The car senses when conditions require the driver to retake control and provides a "sufficiently comfortable transition time" for the driver to do so.
- Level 4²: The vehicle performs all safety-critical functions for the entire trip, with the driver not expected to control the vehicle at any time. As this vehicle would control all functions from start to stop, including all parking functions, it could include unoccupied cars.

NHTSA note three related streams of technological development as follows: i) in-vehicle crash avoidance systems (either warning the driver or involving limited automated technology to control the vehicle); ii) vehicle-to-vehicle communications (developed for crash avoidance); and iii) self-driving vehicles.

¹ Venturer Project Deliverable D1.

² Some other hierarchies separate Level 3 into two extents and identify 'everywhere anytime' automation as Level 5.

1.2 Use Scenarios

There are a number of scenarios under which road-based AVs could operate. In the extreme, AVs might only operate in a system segregated from other, non-autonomously controlled, road users. Alternatively, were they to operate on an existing road network in current types of traffic condition, then they would be subject to interactions with all types of vehicle, driver, cyclist, and pedestrian. These two extremes could hardly be more different in terms of what would be expected of an AV and the ways in which it would have to interact, manage, and negotiate its way through a system.

Throughout this review, consideration is given to the relevance of knowledge about road user interactions as they currently obtain, and which may be relevant to the AV context. For the purposes of this review, therefore, a set of AV Use Scenarios is used to frame the discussion, and to provide a defined scope for understanding the relevance of current research to the AV context. The four Use Scenarios are as follows:

- **Use Scenario 1: Fully segregated AV network** – In whatever form this may be (for example pods or similar vehicles). AVs are completely segregated from other road users and operate within their own system. AVs would interact only with other AVs and the infrastructure of the network.
- **Use Scenario 2: Motorway or expressway network** – This scenario is a situation in which AVs operate alongside human-controlled vehicles, however only within a constrained subset of roads on the general network, i.e. high-volume, high-speed roads and where there may be a significant amount of instrumentation and management (e.g. Smart Motorways). In this scenario AVs will interact with other AVs, human drivers, and the infrastructure of the road network (grade separated junctions with merges and diverges, lanes, signage including variable speed limits), but no intended, or at least very few, non-motorised road users³.
- **Use Scenario 3: Typical Urban network** – This complex scenario comprises the typical roads found in urban and suburban areas and includes arterial roads, distributor roads, high streets, access roads and local streets. There will be a wide range of different types of road user, as well as a need to navigate various forms of junction and other complex infrastructure and a high level of different types of regulation (e.g. speed, parking and loading). AVs will interact with other AVs, human drivers (of a variety of vehicle types including buses, delivery vehicles and taxis), pedestrians and cyclists, and with the infrastructure of the road network (signalised, roundabout and priority junctions, variable numbers of lanes and bus and cycle lanes, regulatory and direction signs, parking areas, a variety of traffic regulation orders, footways and pedestrian crossings).
- **Use Scenario 4: Shared space** – Shared space is an urban design approach which seeks to minimize the separation between different types of users in order to enhance priority for pedestrians and cyclists, which is often absent from much of the public highway. It does this by careful design to reduce motor traffic speeds and usually entails removing features such as kerbs, road surface markings, traffic signs, and traffic lights, and by introducing more subtle and naturalistic forms of speed control through different surface colours and textures and roadside features. Increasing skill and knowledge about the nature of appropriately designed shared space is growing as more schemes are implemented. In this final scenario, AVs will need to navigate an environment which is less well defined and regulated than a typical urban highway network. AVs will be expected to interact with every type of user on an equal basis with no defined priority. AVs will interact with other AVs, human drivers, pedestrians and cyclists.

³ It should be noted that humans may be on the carriageway not as users, but to conduct highway maintenance or assist with vehicle recovery etc. and so even vehicle-only roads cannot be considered as entirely closed to the possibility of necessary or unintended human interaction.

Of course the introduction of new vehicle technology may have implications for the way that we approach the design and management of the infrastructure, but this is beyond the scope of the research. Secondly, the research at hand is connected with the introduction of AVs into the existing highway network where there are human drivers. In this sense we are not so concerned with the Use Scenario where AVs operate on a fully segregated network. Such networks would allow for interesting and radical changes in control and management. For example, in relation to priority junctions (one of the forms of junction control of particular interest when introducing AVs into an existing network), vehicle-to-infrastructure and/or vehicle-to-vehicle communication could be used to place demands into the system for capacity at the junction which are then resolved in order to reduce overall delay (see for example Dresner and Stone, 2005 and Van Middlesworth and Dresner, 2008). These ‘AV system only’ considerations are beyond the scope of this literature review.

The existing road system is hugely complex and well-established, with a vast range of possibilities for different types of interaction. This presents a significant challenge to AVs in terms of safe, efficient and effective navigation through the network. Human drivers and other road users may not behave as AVs might expect (i.e. rationally or in a patterned way), and this variability is perhaps one of the greatest challenges for AV decision systems.

Thrift (2004) suggests that the private car is a deeply ingrained cultural icon. The infrastructure that supports car use is a fundamental part of the fabric of modern life. Even if someone does not drive a car, they are likely to encounter on a daily basis motorised traffic and the road network that supports it. AVs are therefore not only entering a functional system within which humans operate, but they are also entering a system heavily laden with different meanings for different users.

1.3 Autonomous vehicle trials

Research (Trump, 2015) drawing on a wide range of sources has identified six trials of Level 3 AV capability on publicly populated road space. The trials are listed in Table 1.

Table 1 Autonomous Vehicle Trials on Public Road Space

Trial	Location	Trial Environment
Google Self Driving Car Project	Northern California, USA	Urban inc. dual carriageways
Volvo ‘Drive Me’	Göteborg, Sweden	Urban inc. dual carriageways
Audi	Europe and various US States	Urban inc. dual carriageways
SATRE (Platooning Trial)	Europe	Motorways
Singapore Autonomous Vehicle Initiative (SAVI) (<i>planned</i>)	One North Business Park, Singapore	Urban
BMW/Baidu (<i>planned</i>)	Beijing and Shanghai	Urban

(Source: Trump, 2015)

Simonite (2013) reports a presentation made by Chris Urmson, head of Google’s self-drive project in which data from hundreds of thousands of miles of travel shows that Google’s cars accelerated and braked significantly less sharply than when humans were driving, and that the Google car was much better at maintaining a safe distance from the vehicle ahead than human drivers are.

Volvo (2014) reports that their test cars, using technology they call ‘Autopilot’, can follow lanes, adapt their speed, and perform merges autonomously. Further developments (Volvo, 2015) suggest they are ready for public trials, and this readiness is based on complete systems that will ‘fail safe’. Audi has completed a 550 mile ‘piloted’ drive from Silicon Valley to Las Vegas (Audi, 2015). BMW is in partnership with the Chinese search engine Baidu to introduce highly autonomous vehicles into cities in China that have already been tested in Germany (Forbes, 2014).

Tesla (2015) has released an initial version of its 'Autopilot' technology on the Model S vehicle, which is currently available to the public. The Tesla Autopilot feature involves four elements: Autosteer, Auto Lane Change, Automatic Emergency Steering and Side Collision Warning, and Auto Park.

'The latest software update, 7.0 allows Model S to use its unique combination of cameras, radar, ultrasonic sensors and data to automatically steer down the highway, change lanes, and adjust speed in response to traffic. Once you've arrived at your destination, Model S scans for a parking space and parallel parks on your command.' (Tesla, 2015)

1.4 Collisions, conflicts and interactions

Collisions, as with the generality of occurrences of failure, are usually multi-factorial. The majority of collisions on roads are a result of human causes, and usually a combination of more than one type of human error or violation, plus possibly other vehicle and infrastructure factors. The preponderance of human error is well documented and as far back as 1980, Sabey and Taylor (1980, p. 6) found that 'the majority of collisions on the highway have a multiplicity of causes', but that most often a human error or failing was involved, usually as the principal contributing factor. Lajunen *et al.* (2004, p. 231) similarly found that in 90-95% of traffic crashes human actions are a contributory factor, and this is also confirmed by Rumar (1985).

The latest statistics on contributory factors to collisions in Great Britain (DfT, 2015a) suggest that the top five contributory factors are as follows: Driver/Rider failed to look properly, 46%; Driver/Rider failed to accurately judge other person's path or speed, 24%; Driver/Rider careless, reckless or in a hurry, 18%; Poor turn or manoeuvre, 16%; Loss of control, 13%⁴. There are a number of behaviours which might lead to traffic conflicts, for example, violations of the right-of-way, insufficient distance from the preceding vehicle, speeding or poorly adapted speed (Risser, 1985).

Reason *et al.* (1990) developed the Manchester Driver Behaviour Questionnaire, which identified three factors: violations, dangerous errors and harmless lapses. They suggest that errors and violations are distinct classes of behaviour and that they have different psychological origins. They found that violations decline with age whilst errors do not. Men reported more violations than women, but, perhaps, they surmise, because of greater truthfulness, women report more errors than men. The key distinction between violations and errors is that violations have origins in social and motivational factors, whilst errors are related to information processing.

In a follow up study using the Manchester Driver Behaviour Questionnaire, and after no particular interventions to effect any behaviour change, Özkan *et al.* (2006) noted that after three years drivers reported less competitiveness while driving in the after period, but more 'speeding, drinking and driving, driving to wrong destinations and having no recollection of the road just travelled'. Those who reported most change in driving were young males and middle-aged females.

A number of studies have explored issues of attention and distraction, and found that these are regularly associated with collisions and near-misses (e.g. Kountouriotis and Merat, 2016). In a large-scale naturalistic study of driving behaviour, Dingus *et al.* (2006, p. 856) noted that 'almost 80 percent of all crashes and 65 percent of all near-crashes involved the driver looking away from the forward roadway just prior to the onset of the conflict'. Driver distraction has been considered from the perspective of information processing models (for example Multiple Resource Theory (Wickens, 2002) and the Working Memory Model (Baddeley, 1992). In research considering distraction in the context of the task demands of drivers, Cnossen *et al.* (2004) found that certain types of in-vehicle task, such as those most closely related to driving, like map reading,

⁴ Note that the quoted percentages indicate the proportion of collisions the factors occurred in, and the total for all contributory factors will sum to more than 100% because of the multi-factorial nature of collisions.

take priority over others. Loss of focus on the actual driving therefore has significant safety implications, particularly in the case of *visual distraction* where attention is taken away from the road (Kountouriotis and Merat, 2016).

It appears, therefore, that most issues of traffic safety in relation to collisions and near misses are caused by the driver as opposed to a technical failure of the vehicle. Such human factor-related concerns are promoted as a principal reason why governments, including the UK government, are pursuing the agenda of AV development. The Department for Transport states that 'The UK government recognises the potential benefits of driverless and automated vehicle technologies, particularly the potential to improve road safety and reduce casualties' (DfT, 2015b, page 4).

At the same time however, the propensity for unsafe driving and collisions also presents a significant challenge to AVs in any use scenario in which they must share the road space with human drivers, because, under such conditions, the AVs themselves will be at risk of being involved in a collision or other unsafe situation which is the result of human error, and over which they may have little control. Therefore understanding unsafe driving practices is important so that AVs may be equipped with the necessary technology and decision systems to respond in the most appropriate way when confronted with potentially hazardous situations.

A distinction is necessary between traffic 'conflicts' and traffic 'collisions'. A simple method of drawing the distinction is to say that traffic conflicts are situations in which there is the *potential* for a traffic collision to occur, however not all traffic conflicts necessarily result in a collision (for example if a driver takes corrective or evasive action); traffic collisions are therefore the result of *unsuccessfully resolved* traffic conflicts (Risser, 1985). Svensson and Hydén (2006, p. 380) define a traffic conflict as 'A situation where two or more road users approach each other in time and space to such an extent that a collision is imminent if their movements remain unchanged.'

The challenge to understanding conflict as a form of traffic interaction is that the majority of examples go unobserved because, suggest Svensson and Hydén (2006), researchers tend only to focus on the significant conflicts (i.e. those which do result in collisions). Figure 1 and Figure 2 below present different versions of the pyramid which represents the continuum of interactions between road users.

Figure 1 - The pyramid—the interaction between road users as a continuum of events (Hydén, 1987)

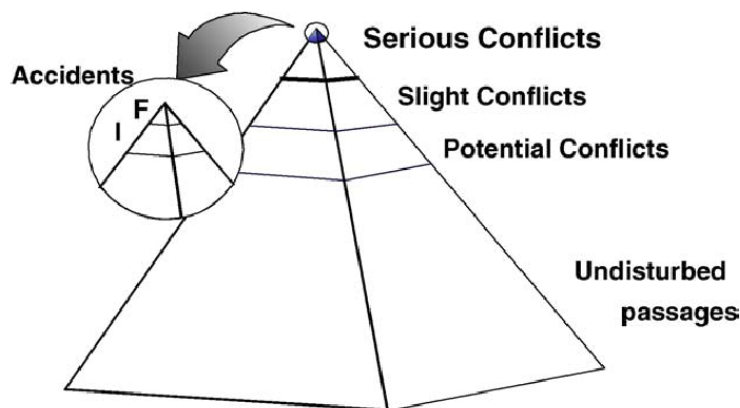
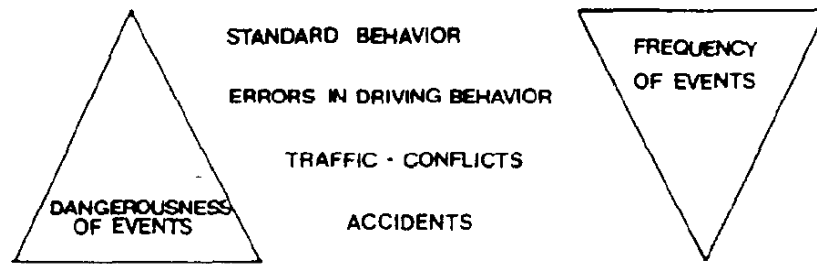


Figure 2 - The steps from behaviour as defined by a norm to actual accidents (Risser, 1985)



The volume inside the bands within the pyramid in Figure 1 is a proxy for the number of incidents of the type described. So far as Figure 2 is concerned, standard behaviour is very common, as depicted by the width of the frequency of events triangle, and the 'dangerousness of events' is, by contrast, low. Frequency and danger reverse as progression is made towards 'accidents'.

The majority of existing knowledge about road user interactions (especially empirical knowledge) focusses on serious conflicts and collisions, whilst the bulk of everyday road user interaction simply occurs without incident and are thus not of particular interest from a traffic safety perspective. They may, however, be of interest from the point of view of user experience (particularly non-motorised users) - the experience of interactions may be unpleasant, hence encouraging / discouraging certain behaviours / infrastructure designs. Even in studies relating to conflict, Bagdadi (2013) points out that the research explores the severity of traffic conflict in order to estimate the crash risk (but not typically the severity of the consequences of a potential crash). However, understanding these unremarkable 'everyday' interactions is of importance to an AV, which will be encountering these typical driver behaviours and interactions on a routine basis.

1.5 Summary and structure of remainder of the review

There are four levels of autonomy and we have identified four different use scenarios. The different categorisations of interaction possible are therefore myriad. A number of trials are already ongoing with different levels of autonomy in various parts of the world. There are various levels of interaction ranging from undisturbed but proximal passing, through increasing levels of conflict where greater degrees of avoidance are required, through to conflicts which result in collisions. Conflicts that do not result in collisions may still be unpleasant.

Traffic engineering is based on the design of highway layouts and control systems to assist in managing interactions between different road users to maximise capacity and ensure safety. Salter and Hounsell (1996) point out that these interactions occur when traffic streams (including pedestrians within the definition of traffic) merge, change lane, or where there are crossing conflicts. This review is concerned predominantly with these types of traffic interaction, or more precisely, how road users perceive, assess, and respond to other roads users within the context of the road infrastructure. We discuss vehicle-to-vehicle and vehicle-with-infrastructure interactions in the next section, and this is followed by discussion of vehicle-with-cyclist interactions and finally vehicle-with-pedestrian interactions.

2 Vehicle-to-vehicle and vehicle-with-infrastructure interactions

This section draws out relevant themes and issues related to current understanding of interactions between vehicles (i.e. vehicle-to-vehicle interactions), and also interactions between vehicles and infrastructure.

2.1 Typology of interactions

Driver interaction sits within a well-established body of theory and research. There are a number of different categories of interaction that drivers might have with either other vehicles or with the infrastructure of the road network.

This review of AV interactions with vehicles and infrastructure deals initially with links (sections of road between junctions). It then moves on to discuss the different types of junctions and their control (Give way junctions, roundabouts, grade-separated junctions, signal-controlled junctions, shared space). There is then a section dealing with traffic signs and regulations. The review then moves in a rather different direction, away from traffic engineering related research to focus on the types of social interaction which take place within the road environment. In particular, we discuss the issue of co-operation and conflict, which in the extreme leads to so-called 'road rage'.

2.2 Links

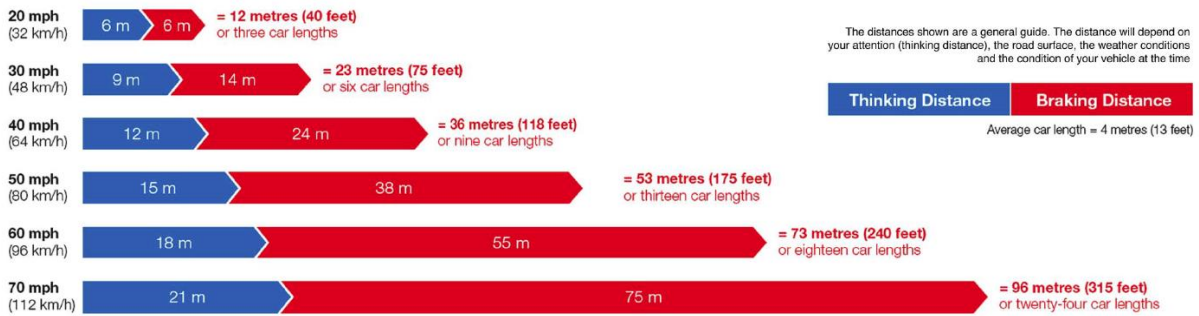
Links are the sections of roads between junctions. There are a number of types of possible interaction on links, for example: following vehicles (maintaining safe stopping distance), overtaking (either using overtaking lanes on dual carriageways, or using the part of the carriageway usually used by oncoming traffic on single carriageways), reading and interpreting signs, observing speed limits, observing lane markings, and using the hard shoulder.

Rule 126 of the Highway Code concerns stopping distances, and states that a driver must be able to stop within the distance ahead that can be seen to be clear (DfT, 2016). Therefore a driver needs to maintain speed such that they ensure that: (i) there is sufficient space between their vehicle and the vehicle in front to avoid a collision in the event that the vehicle in front stops suddenly, and (ii) that they are not travelling at a speed which would prohibit them from successfully navigating the infrastructure, for example when arriving at a junction.

This rule is similar to the Assured Clear Distance Ahead rule (ACDA) which is used in other countries such as the United States of America (for example see: Leibowitz *et al.*, 1998, p. 93): 'The ACDA rule holds the operators of a motor vehicle responsible to avoid collision with any obstacle which might appear in the vehicle's path.'

The Highway Code provides a series of modifiers to this general rule around stopping distance, which are applicable in specific contexts as follows: (i) when travelling on roads which carry faster-moving traffic, the Code stipulates a two-second gap between a driver and the vehicle in front (this tolerance is doubled to four seconds under unfavourable conditions such as wet roads, and increased further still in icy conditions); (ii) the Code states that a larger gap should be given by drivers of heavy or large vehicles and motorcycles, which require greater distance to stop; and (iii) drivers of large vehicles while driving in a tunnel should leave a four-second gap between their own vehicle and the vehicle in front (DfT, 2016).

The Highway Code suggests the following braking distances for human-controlled vehicles at varying speeds:

Figure 3 - Example stopping distances presented in the Highway Code (DfT, 2016)**Typical Stopping Distances**

Whilst the driver of a vehicle is responsible for maintaining the stopping distance in front of his or her vehicle, they have little to no control over the stopping distance that the driver behind them has adopted. Discussion below considers aggressive driving behaviours such as tailgating. While a human driver may attempt to compensate by providing a braking distance ahead of him or her which is the equivalent for two vehicles (i.e. their own vehicle and the vehicle which is dangerously tailgating), it is unclear how an AV would manage an interaction in which another road user was not following the rules in this way, and hence placed the AV and its occupants in the hazardous position of increased potential for a rear-end collision if it were forced to stop suddenly.

An AV's enhanced proficiency at braking might also present a challenge in a mixed-traffic context. Figure 3 shows the perception and reaction distances of human drivers (the 'thinking' distance). In general, and assuming sufficient levels of information always being available to the AV and sufficient computing power to make appropriate decisions, AVs will have better (and more consistent) perception and reaction times than their human counterparts. This is a desirable road safety outcome in terms of AVs' ability to come to a halt more quickly and safely than a human driver, and thus avoid collisions with unexpected obstacles in the vehicle's path. However, in certain scenarios (the close following example above), an AV stopping more efficiently than a human driver, and without recognition of the unfolding situation behind the vehicle, may exacerbate the possibility of collisions.

Hardy and Fenner (2015) investigated the contribution of Level 2 automation (automation based on driver assistance such as co-operative adaptive cruise control (CACC) and collision mitigation braking (CMB)) to mitigate congestion levels and poor journey time reliability, collision rates, carbon dioxide emissions and poor journey time reliability. CACC has the ability to create uniform headway and similar velocities throughout a platoon. They studied four scenarios as follows: i) Vehicles have the same braking performance but 0.3 second vehicle-to-vehicle transmission lag exists; ii) The platoon leader has a 25% braking performance advantage compared to the follower, and V2V lag exists; iii) The platoon leader has a 25% braking performance advantage compared to the follower, but V2V is lag free; and iv) The platoon follower has a 25% braking performance advantage compared to the leader, and V2V lag exists. They estimated that the two lane A14 between Huntingdon and Cambridge could have its capacity increased from its notional present capacity of 3600 vehicles per hour (vph) to 9200 vph. They also estimated carbon emissions reductions of up to 43%.

AVs will obtain data on their surroundings and take decisions about stopping distances and whether to overtake or not based on their ability to safely stop or complete an overtaking manoeuvre. A specific issue, and hence research question, relating to interactions however is as follows: **What decision making behaviour may be required of an AV to deal with aggressive behaviour of a human driver in a following vehicle?**

2.3 Junctions

Junctions are the nodes within a transport network. For a simple four-way junction there are sixteen crossing conflicts, eight diverging conflicts and eight merging conflicts. This number of conflicts may be reduced in number and modified in nature by creating different types of layout, such as a roundabout or grade separation, or by separating the conflicts in time by using traffic signal control.

Drivers may retain the right of way at a junction, for example, by virtue of being on the main road through a priority junction. Otherwise, they may be required to give way (yield priority) to other streams of traffic either at priority junctions or roundabouts. There remain a significant number of four-way intersections in the UK, particularly in housing estates constructed in the 1950s and 1960s, where there may be no marked priority for one stream of traffic over another. In addition, a variety of shared space schemes being constructed according to current practice similarly, and deliberately, do not provide clear priority for one stream of traffic over another, or for motor traffic over pedestrian traffic, or vice versa. There is no general application of what would be the equivalent of the 'priority to the right' rule in the UK, as stipulated in Article 18.4.a of the Vienna Convention on Road Traffic for countries where traffic keeps to the right. Instead, such unmarked junctions operate informally on the basis of 'first come-first served'. At a different extreme, drivers may be subject to control where their right of way is temporarily prohibited by a red aspect on a traffic signal head. When on green, the driver is permitted to proceed if the way is clear. At grade-separated junctions, drivers will merge with other traffic as they join a traffic stream on the main line carriageway, or diverge if leaving the mainline carriageway. Ultimately, for full automation to be achieved, solutions will need to be developed for all these circumstances.

For countries that do apply a 'priority to the right' rule in circumstances where priority is not explicit, De Ceunynck's *et al.* (2013) field studies have relevance. They investigated the differences in interactions and behaviours of drivers at junctions where there is priority control relative to situations where the priority to the right rule applies (in a context in which right-hand rule of the road was obtained). They found significantly more violations (27% of all interactions) where the priority to the right rule applies than where the junction was controlled by priority (8% of all interactions). They suggested that there was in fact an implicit rule of first-come-first-served at priority to the right junctions and the characteristics of the approach to the junction (e.g. whether an approaching vehicle stops or not, and its deceleration characteristics) are relevant to the subsequently observed order of procedure of the different approaching vehicles through the junction.

2.3.1 Priority junctions

The most common type of intersection is the priority junction. While no four-way priority junctions are now constructed in the UK, perhaps with the exception of schemes which are shared space, there is a legacy of many thousands of priority junctions of this type. At certain, mainly rural, locations, where speeds and volumes on the main road may be higher, it may be desirable to create a stagger so that the minor road traffic crossing the major roads first turns right on to the main road and then turns left off the main road. In a left-hand rule of the road country, right – left staggers are preferred to left – right staggers so that crossing traffic does not queue on the major road in order to leave it, and so that the right-turn manoeuvres off the major route are outside the stagger.

An important feature of a priority junction, and one that is returned to later in the review, is that road users must give way to pedestrians who have started to cross the side road (DfT, 2016, Rule 170).

On the basis that there is no absolute control (red/green) of the vehicle stream that is giving way, drivers will need to make decisions about when to cross or join a traffic stream. They will be seeking and accepting gaps in the traffic stream which are sufficiently long (in terms of time and distance) for them to safely make a manoeuvre without causing conflict and while also providing a margin of safety. Gap acceptance is about

deciding between two options as follows: (i) accepting the gap is large enough for the manoeuvre they plan to undertake, or (ii) rejecting the gap for the manoeuvre they plan to undertake. Typically, a driver will reject many gaps before accepting a gap (Salter & Hounsell, 1996).

A gap is the period of time between the arrival of two major road vehicles (either heading in the same direction, or heading in opposite directions) at the junction where a minor road vehicle is attempting to cross or enter one or other of the traffic streams. A lag is the unexpired portion of a gap which is still available to a minor road driver when they arrive at a junction. If a minor road vehicle arrives at a junction with a major road and there is a sufficiently long lag time period, the driver may enter the major stream immediately. On the basis that such a driver may in effect have a rolling start, it is likely that smaller lags are accepted than subsequent gaps, where the vehicle entering is doing so from a standing start.

The probability of gaps in a traffic stream of a certain period may be found from the exponential distribution, and the willingness to accept gaps of different size by drivers conforms to the Normal Distribution. The identification of the critical gap, usually defined as the shortest gap that 50% of drivers would accept, may be determined from observation. For design purposes, it is usually the case that empirical models are estimated based on observation, geometry and conflicting flow (Kimber and Coombe, 1980).

While Harrell and Spaulding (2001) found, from simulations, the size of the approaching vehicle to be relevant in gap acceptance decisions, Hanowski *et al.* (2007) rather conversely found from real world observations that, where incidents occurred between light vehicles and heavy vehicles, it was aggressive driving on the part of the light vehicle driver that was the primary contributing factor⁵.

Gstalter and Fastenmeier (2010) developed a taxonomy of driving tasks, definitions for correct behaviours and errors in behaviour, and methods for observing these differences. This allowed for the ratio of errors committed by observation in the field relative to the number of opportunities for the errors to be estimated. They compared the reliability of drivers at different types of intersection and found that the highest numbers of errors occurred at priority junctions and roundabouts. They found that older drivers' error ratios in nearly all tasks are significantly higher than those of the other groups. An interesting research question is as follows: **As a result of their greater predictability, will the presence of autonomous vehicles introduce a degree of additional control into the vehicle mix, resulting in fewer errors by drivers?** This is beyond the scope of this project, however, as it would require multiple autonomous vehicles to be available in the field for testing.

Dukic and Broberg (2012) found that older drivers, while also having less neck flexibility than younger drivers, tended to look more at lines and markings in the road while younger drivers tended to look more at other vehicles.

Wickens *et al.* (2001) proposed a model to explain the selection of visual information in different areas of interest (AOI) that may be looked at during multi-tasking based on four factors as follows: Expectancy (the quantity of relevant information expected in the AOI); Value (the relevance of a piece of information); Saliency (high visual saliency may have low relevance to the task and is hence a source of bias); Effort (the cost of a saccade⁶ between AOIs). Using only different levels of control on the approach to an intersection (stop, priority and yield (in this context yield may be understood as merge) as a measure for Value and different flow volumes on the road to be joined as the variable for Expectancy, Lemmonier *et al.* (2015) found that dwell time looking at the intersecting road was around 10% of all observation time for all intersecting road flow levels with a stop line. With a priority-controlled crossing, dwell time on the intersecting road

⁵ Notably, however, commentators explained a first recorded collision between an AV car (operated by Google) and a human-driven bus in terms of the bus driver expecting that the smaller vehicle would give precedence to the larger vehicle whilst the AV system was seeking to change lane to circumvent an obstruction.

⁶ A saccade is a quick eye movement between two or more fixed points.

increased to only around 20% for a situation with no intersecting road flow and to 40% where the intersecting road flow was light or heavy. For a yield, the dwell time on the intersecting road was between 35 and 40%.

Approaches to estimating capacity do not attempt to understand the decision making process, which is clearly variable based on a range of possible factors. Harrell and Spaulding (2001) suggest that the decision to accept a gap or not is related to the value of undertaking the manoeuvre relative to the potential cost of undertaking the manoeuvre and use as a basis the model of Gray and Tallman (1984). Equation 1 below shows the form that they adopted.

$$\frac{P_t}{1 - P_t} = a \cdot \left(\frac{(1 - P_{cg}) \cdot G}{P_{CS} \cdot S \cdot P_{CM} \cdot M} \right)^b$$

Where

P_t = probability of undertaking a turn

P_{cg} = probability of a collision for a given gap

G = size of gap

P_{CS} = Probability of collision given the speed of the oncoming vehicle

S = Speed of oncoming vehicle

P_{CM} = Probability of collision given size of oncoming vehicle (mass)

M = Mass of oncoming vehicle

a, b = coefficients to be estimated

The ratio of the probability of undertaking the manoeuvre to the probability of not undertaking the manoeuvre (the left hand side of the equation) is a function of the ratio of the 'value' of making the manoeuvre (numerator on the right hand side) to the 'cost' of making the manoeuvre (denominator on the right hand side). The 'value' of making the manoeuvre is expressed as the probability for a given size of gap of the manoeuvre being collision free. The 'cost' of making the manoeuvre is expressed as the product of the probability of a collision for a given approach speed and the probability of a collision for a given approach vehicle size. Using data from a driver simulator where test drivers were asked to make a left turn (right hand rule of the road), they demonstrated that such an approach explains 67% of the variation in the data, and this is more than is explained by linear models.

When an AV approaches a junction it will be posed with the same gap or lag acceptance scenario as a human driver. The technology of the AV may allow it to make a decision about gap acceptance more reliably than a human driver. This is because it ought to be able to more reliably determine the approach speed and the distance of the approaching vehicle. Its decision making processes will also not be subject to the value of the ratio of the gains of making a turn relative to the losses, as expressed in Equation 1. It will be programmed to accept turns where the probability of a collision is below a certain threshold (the probability being estimated from the known variability in its ability to detect the speed and distance of an approaching vehicle). However, it is a moot point as to whether the behaviour of the AV should in fact mimic human decision making when in traffic conditions mixed with human drivers. An AV-like, rather than a human behaviour like approach, may result in less violation of the rules of the road by other drivers in the vicinity of the AV.

Existing research suggests that gap acceptance is a well-established aspect of driver behaviour, and furthermore one which is understood and negotiated tacitly between drivers (i.e. a driver in the major stream who sees a vehicle in a minor stream at an intersection will have certain expectations about how that driver will behave, what gap is acceptable and so on). Therefore in order to manoeuvre safely and successfully it may be the case that an AV will need to interact in a way that human drivers in the major stream are *expecting* when they see a vehicle at an intersection ahead of them attempting to join their flow. An appropriate

research question to ask is therefore: **Do approaching AVs, when they are clearly distinguishable as such, engender a different gap acceptance behaviour amongst other road users, at priority junctions?**

2.3.2 Roundabouts

Empirical models based on geometry and flow for the estimation of capacity of roundabouts were developed by Kimber (1980). These, together with the formulae for priority junctions in Kimber and Coombe (1980) are the basis for JUNCTIONS, the Transport Research Laboratory software used to analyse priority and roundabout junctions.

Troutbeck (1990) studied roundabouts in Australia and found that the gap acceptance behaviour of drivers changes with increasing circulating flow: rather than priority being ceded by entering traffic, as flows grow, merging behaviour tends to take place. Merging and subsequent weaving tends to take place at large roundabouts and this mechanism is discussed more in the following section.

Despite Troutbeck's early suggestions, the majority of behaviour at roundabouts is related to gap acceptance and this is therefore similar to behaviour at priority junctions. The relevant research question is therefore as follows: **Do approaching AVs, when they are clearly distinguishable as such, engender a different gap acceptance behaviour amongst other road users, at roundabouts?**

2.3.3 Grade separated junctions

There are four possible ways in which drivers may behave at a merge, as described by Cowan (1979) as follows: (a) First come, first merged; (b) Alternate merging; (c) Partial priority given to one lane⁷; and (d) Priority given to one lane (the queue in the priority lane discharges before the other lane can discharge).

The UK Highway Code (DfT, 2016, Rule 259) states that traffic entering a motorway should give priority to traffic already on the motorway. The way that such merges work is in fact a mix between Cowan's type (c) and type (d) merge. Again, rather than design based on gap acceptance theory, the approach adopted in the UK is based on design charts which demonstrably work from an empirical point of view (Highways England, 2006).

Grade separated junctions occur mainly on motorways and expressways (Use Scenario 2) and in higher speed conditions. The relevant research question is therefore as follows: **Do approaching AVs, when they are clearly distinguishable as such, engender a different gap acceptance behaviour amongst other road users, at merges?**

2.3.4 Signal Controlled junctions

Drivers approaching signal control have to make a decision about whether or not to proceed based on the signal aspect displayed to them. These are likely to be as follows i) proceed based on a green aspect, ii) brake when an amber aspect begins to be displayed, iii) brake on approaching a red aspect, iv) brake on approaching the end of a queue waiting at a red aspect. The most complex decision is related to the appearance of an amber aspect at the end of a green period, scenario (ii). Depending on the distance of the driver from the stop line and the driver's speed at the time of the change to amber, the driver may decide to proceed through during the first fractions of a second of an amber aspect in order to avoid uncomfortable braking. This behaviour may also be associated with a slight acceleration in order to ensure the junction is cleared before the subsequent traffic phase begins to move. A similar acceleration may also be evident in

⁷ A major stream vehicle with a headway gap ahead of it may have this gap filled by an entering vehicle, but the reduction in headway in front of the major road vehicle will not reduce below the minimum headway.

behaviour associated with proceeding on a green aspect if the driver thinks that the traffic signal may be about to change to amber.

Liu (2007) studied factors that affect approach speed to signal controlled junctions. He constructed a binary logistic regression model to predict whether the speed limit was broken on the approach and found that violation was six times as likely in suburban as compared with urban settings, three times as likely when in a non-peak period as opposed to a peak period rush-hour or not, and male drivers under 55 years of age had the greatest speeding propensity. The signal aspect on approach, however, was the most significant determinant of speed, with lower speeds observed when the aspect was amber.

On the basis that signal control, by definition, effectively provides ‘instruction’ as to how to behave, there is less variability in behaviour and therefore less of a need to research the interactions between different types of road user and AVs. Contrariwise, there could be the risk that a human driver following an AV in a scenario where the green phase is closing down to amber may assume the AV will consume the benefit of the amber and seek to follow through by close following.

2.3.5 Modern street design and shared space

The approach to designing residential roads in the UK has changed since the publication of *Manual for Streets* (CLG/DfT, 2007). The manual has an emphasis on good overall design, without undue or singular focus on the movement function of residential streets. The philosophy is to give a higher priority to pedestrians and cyclists because these types of users are able to create more of a sense of place and community. The research that underpins the manual (York *et al.*, 2007) has found that reducing width and visibility reduces speeds, and it remains the geometry of links and junctions, rather than the more qualitative characteristics of the junction (its age, or other features) which primarily determine speed and likelihood and severity of collisions. The research found that, with no other speed reducing measures, stopping distances above 20m retain a margin of safety in the residential roads studied. They also found that parking on the carriageway reduces speeds by 2 to 5 mph and that reducing lines of sight from 120m to 20 m reduces approach speed by 20 mph on links and 11 mph at junctions. The principles enshrined in *Manual for Streets* are now also receiving wider application on non-residential roads in urban areas such as high streets (CIHT, 2010).

Hamilton-Baillie and Jones (2005) report examples from Continental Europe and the UK where the removal of separation between traffic and people is making streets safer and less congested. These approaches are usually accompanied by wider urban realm improvements which include the removal of kerbs, barriers, highway signs and road markings. Such shared space schemes remain in their infancy in the UK, but experience is growing and there is a realisation (see for example Parkin and Smithies, 2012) that there are significant subtleties to the good design of shared space schemes which require attention to the visual and tactile messages that they provide to all road users about the speed that they should adopt and the positioning and routeing within the shared space that they should take.

There are shared space schemes which are rightly being questioned in terms of their efficacy, however. For example, Moody and Melia (2014) seek to challenge the evidence relating to the effectiveness of one of the early shared space scheme designs in Ashford in Kent.

An obvious and specific question in relation to Use Scenario 4 shared space situations is in relation to the way that AVs would react to and behave where there is no clear priority. The relevant research question is: **How will AVs behave in shared space?**

2.4 Signs and traffic regulations

In areas other than those which are deliberately designed to be relatively free of specific regulation, such as shared space, the road remains a highly regulated part of the public realm. Regulation is conveyed to drivers

through signing and markings. AVs would of course, based on appropriate levels of information and communication received, need to respond to this regulation in a precise and conforming way. Human drivers, on the other hand, are much more variable in their compliance with regulation. Summala & Hietamäki (1984) found for example that drivers' responses to road signs were variable and they recalled road signs better when they were more relevant to them.

There are occasions when regulations as specified need to be reinforced with on-road systems to identify and fine drivers as a way of helping to enhance compliance. These are often in the form of cameras directed at, for example, red signal compliance at signal controlled junctions, bus lane enforcement and, perhaps most ubiquitously, speed enforcement. Clearly, again, one of the major benefits of AVs will be their inability to progress at more than the posted speed limit, and speed limiting to the posted limit arguably should be one of the first and most important features of semi-autonomous vehicles.

Schechtmana *et al.* (2016) sought drivers' views in parallel with the implementation of speed enforcement cameras. The majority of drivers (61%) predicted a positive impact of speed cameras on safety and suggested that enforcement is the main reason for speed limit adherence. Exceeding the speed limit was reported by 38% of drivers at the beginning of the study and by 11% after the introduction of the enforcement. They also found that accuracy of knowledge of the imposed speed limit were themselves limited. Linked with the findings of Reason *et al.* (1990) that errors and violations are distinct classes of behaviour with different psychological origins, we can expect that, for example, as violations decline with age, so will speeding.

AVs will need to recognise situations where there are roadworks and, in particular, there may be a need for on-board systems which take in information from the road in order to be in a position to override pre-programmed information about the nature of the road network, which may be temporarily inaccurate, for example different speed limits. The need to respect the safety of maintenance teams has already been noted earlier. Variable Matrix Signals or Variable Matrix Signs may be used to provide guidance or instruction. There may be temporary lane closures or derogations from, for example, 'keep left' signs where traffic is directed around the right hand side of a traffic island.

2.5 Social interactions in the road environment

Wilde (1976) studied social interactions in relation to driver behaviour. He suggested that, despite the degree of anonymity that might be presumed to be available to all types of road user, participation in traffic does not in fact take place in a social vacuum. Individual performance of the functions relating to road use takes place in the context of a collective of road users, and this collectivism may be characterized by social habits and social values, by certain expectations, and by methods of communication. He did also note that there are deviations from what may be regarded as social norms evident in the behaviour of road users.

Havârneanu and Havârneanu (2012) studied the ways in which road users respond to the rules of the road when they appear to be perverse. In particular, they studied the reactions of drivers in situations where the rules have no apparent safety benefit. Unsurprisingly perhaps, they found that when there is a lack of evident factors which increase risk, drivers are more likely to violate rules of the road. Legree *et al.* (2003) found that stressful situations increase crash risk. Earlier, Sorock *et al.* (1996) had studied motor vehicle crashes in roadway construction zones, which do indeed add stress and risk for drivers on roads.

2.5.1 Conflict ('road rage')

An important issue in understanding driver interactions is that of aggressive driving behaviours and what is commonly termed 'road rage'. Research suggests that aggressive driving behaviours are relatively common, and thus it follows that an AV must be able to recognise, at least in terms of a behaviour pattern, and respond in an appropriate manner to instances where rational behaviour is overtaken by emotional responses on the

part of other drivers. A report by the American Automobile Association (AAA, 2009, p. 10) notes that ‘surveys consistently show that people believe aggressive driving is one of the most serious traffic safety problems’. This perception of aggressive driving suggests that it is an area of particular concern in terms of AV interactions with other vehicles on the road network.

A distinction may however be drawn between aggressive driving and road rage. Road rage is usually taken to mean an incident in which a driver takes actions *with the specific intention of harming another road user*, whilst aggressive driving is engaging in dangerous or forceful manoeuvring of the vehicle but without the specific intention to harm someone else (Schafer, 2015). Whilst both forms of behaviour are similar in that they place others at significant risk, the distinction is merited because of the differences in motivation, driver personality, and outcomes of each behaviour (Schafer, 2015; Hennessy, 2011; Miles & Johnson, 2003). A distinction between aggressive driving and road rage behaviours is also necessary from a legal perspective, where the former are treated as a subset of traffic violations, whilst the latter are regarded as criminal acts in the manner of physical assaults (Schafer, 2015; Sanders, 2002).

The definitions of what constitutes an incident of road rage or aggressive driving continue to be debated in studies which focus on the subject. For the purposes of this review it is sufficient to refer to Schafer’s (2015, p. 12) three categorisations of drivers’ aggression, included in Table 2:

Table 2 - Typology of driver aggression

Type	Definition	Examples of behaviour
Aggressive Driving	‘Time-urgent and self-oriented behaviours that can be dangerous, illegal, and warrant concern from other motorists, but lack harmful intent’ (Hennessy & Wiesenthal, 2005, p. 62)	Speeding Frequent lane changing Passing on the hard shoulder Cutting corners
Road Rage	Purposeful infliction of harm (physical or psychological, injury, humiliation, or annoyance) on another within the driving environment in direct response to a perceived injustice (Hennessy & Wiesenthal, 2005)	Sounding the horn aggressively Gesturing/shouting Flashing lights aggressively Cutting up Tailgating Sharp braking Following Blocking
Violent Road Rage	An assault with a motor vehicle or other dangerous weapon by the operator or passenger(s) of one motor vehicle on the operator or passenger(s) of another motor vehicle caused by an incident that occurred on a roadway’ (NHTSA, 2000)	Violent confrontation Deliberate collision Forcing another vehicle off the road

Many of the examples of behaviour described in Table 2 have the potential to present a challenge to an AV in the way it interacts with other vehicles.

All types of driver aggression have at their core the manifestation of a driver's negative emotional state (typically anger) in their driving behaviour. Jonah (1997) has described the aggression, frustration, and impatience involved in aggressive driving. Aggressive driving has also been linked to impulsivity, sensation seeking, and a person's propensity for boredom (see: Dahlen *et al.*, 2005). This suggests that whilst aggressive driving is a relatively patterned behaviour in psychological terms, its occurrence on the roads is dependent to a greater degree upon the emotional state and personality traits of individual drivers, and therefore their occurrence is unpredictable. However, it is also clear that there will be situations in which drivers might be particularly prone to experiences of boredom, stress, or anger – such as in heavy traffic or in restrictive speed limits – and thus it might be possible for an AV to identify particular circumstances in which the potential for an encounter with an aggressive driver is higher.

Actual violent road rage incidents in which a driver physically assaults another road user are suggested to be very rare (Schafer, 2015; Smart & Mann, 2002; Wickens, 2011), particularly in the context of the whole range of vehicle collisions. For example, Sansone and Sansone (2010) found that just 2% of drivers had admitted causing harm (or attempting to cause harm) to other drivers. Joint (1997) similarly suggests that only 1% of drivers in a study commissioned by the Automobile Association (AA) had experienced physical assault by another driver.

However, beyond direct physical assaults, incidences of aggressive driving and road rage are extremely common, and their implications for road safety very serious. For example, a study of aggressive drivers in Malaysia by Sullman *et al.* (2015) found that all of their measures of aggressive expression were significantly associated with crash-related conditions, including: losing control of the vehicle, loss of concentration, and having near misses.

A number of studies report different figures for levels of aggressive driving, but all are consistently high. Several examples are given below:

- Joint (1997) reported UK data from the AA suggesting that 90% of motorists had experienced road rage in the past year, and that 60% of people had admitted to engaging in the behaviour: 62% had engaged in aggressive tailgating, 59% in aggressive headlight flashing, 45% had made obscene gestures, 21% had deliberately obstructed another vehicle, and 16% had been verbally abusive.
- The Royal Society for the Prevention of Accidents (RoSPA, 2011) report on inappropriate speed has found that inappropriate speed is responsible for approximately 14% of all injury collisions, 15% of serious injury collisions, and 24% of collisions resulting in death in the UK. The study also noted that speeding drivers were more likely to be recorded as undertaking 'aggressive driving', being 'careless, reckless or in a hurry' or 'impaired by alcohol' or having 'stolen a vehicle'. The report suggests that there is a 'link between excess speed and other types of risk-taking behaviour' (p. 4).
- A large-scale international Gallup survey of 23 countries worldwide in 2002/03 identified that levels of aggressive driving vary greatly by country. In the US, 66% of drivers had been subject to aggressive behaviour from other drivers in the past 12 months. This figure was 65% in Russia, 51% in Australia, 48% across the participating European countries, 37% in Argentina, and just 26% in Japan. The vast majority of participants in this study also perceived that aggressiveness of fellow drivers had increased in recent years.
- Asbridge *et al.* (2003) reported that 74.3% of drivers surveyed in their Ontario study had perpetrated road rage, and 52.8% had been victims of road rage. Road rage offending was predominantly a male activity, while there were no gender differences in victimization. Moreover, road rage was not isolated among young adults; rather, road rage was prominent across all ages, with the exception of seniors. Consistent with the existing literature, road rage was found to be higher in urban settings.
- Dąbrowski (1998) suggests that 80% of drivers in Poland experience road rage at least once a week.

- Dukes *et al.* (2001) reported an estimate from the US Department of Transport that as much as two thirds of the 41,907 deaths as a result of vehicle collisions in the US in 1996 could be attributed to aggressive driving. Furthermore, the study goes on to suggest that at the time aggressive driving behaviours were increasing significantly.
- In the USA, a report by the American Automobile Association (AAA, 2009, p.10) suggests that 56% of collisions which result in death involve 'one or more unsafe driving behaviours typically associated with aggressive driving'.

Numerous other sources suggest similar findings. Aggressive driving behaviours and road rage pose a risk to the safety of road users, and this will also pose a challenge to AVs. Aggressive driving and road rage are human phenomena, and it is unclear as to whether the presence of AVs in the vehicle mix will either have a neutral effect on the level of road rage (extent and intensity) or whether they will serve to ameliorate the problem or exacerbate the problem. They are a product of psychological traits and drivers' emotional states, and as such are prone to unpredictability.

Neale *et al.* (2006, xxiii) undertook a naturalistic driving study and some of the most important findings addressed as part of the high priority goals analyzed for this report are presented below:

- This study allowed, perhaps for the first time, the capture of crash and collision events that included minor, non-property-damage contact. These low severity collisions provide very valuable information and occur much more frequently than more severe crashes. As a result, crash/collision-involvement was much higher than expected in that 82 total crashes/collisions reported in that study, while only 15 of these crashes were reported to the police. For urban/suburban settings, this suggests that total crash/collision involvement may be over five times higher than police-reported crashes.
- Almost 80 percent of all crashes and 65 percent of all near-crashes involved the driver looking away from the forward roadway just prior to the onset of the conflict. Prior estimates related to 'distraction' as a contributing factor have been in the range of 25 percent.
- Inattention, which was operationally defined as including: (1) secondary task distraction; (2) driving-related inattention to the forward roadway (e.g., blind spot checks); (3) moderate to extreme drowsiness; and (4) other non-driving-related eye glances, was a contributing factor for 93 percent of the conflict with lead-vehicle crashes and minor collisions. In 86 percent of the lead-vehicle crashes/collisions, the headway at the onset of the event was greater than 2.0 seconds.
- For scenarios involving conflict with a lead vehicle, the most frequent cases of lower severity conflicts (i.e., incidents and near-crashes) occurred in lead-vehicle moving scenarios, while 100 percent of the crashes (14 total) occurred when the lead vehicle was stopped. This indicates that drivers have sufficient awareness and ability to perform evasive manoeuvres when closing rates are lower and/or expectancies about the flow of traffic are not violated.
- The rate of inattention-related crash and near-crash events decreases dramatically with age, with the rate being as much as four times higher for the 18-to-20 age group relative to some of the older driver groups (i.e., 35 and up).
- The use of hand-held wireless devices (primarily cell phones but including a small amount of PDA use) was associated with the highest frequency of secondary task distraction-related events. This was true for both events of lower severity (i.e., incidents) and for events of higher severity (i.e., near-crashes). Internet-enabled devices were also among the categories associated with the highest frequencies of crashes and minor collisions, along with looking at/reaching for an object in vehicle and passenger-related secondary tasks.

- Drowsiness also appears to affect crashes and collisions at much higher rates than is reported using existing crash databases. Drowsiness was a contributing factor in 12 percent of all crashes and 10 percent of near-crashes, while most current database estimates place drowsiness-related crashes at approximately 2 to 4 percent of total crashes.
- The lead-vehicle crash and near-crash data clearly shows that development of purely quantitative near-crash criteria (i.e., not requiring at least some degree of verification by a human analyst) is not currently feasible. A primary reason for this was that vehicle kinematics associated with near-crashes were virtually identical to common driving situations that were not indicative of crash risk. Thus, qualitative and quantitative criteria are dependent upon one another to some degree. Fortunately, advances in digital video compression and storage technology, and the advancement of data reduction software, have made video verification feasible for large numbers of events.
- Results from the analysis investigating driver adaptation to instrumented vehicles indicate that even when the same driver was switched from a private vehicle to a leased vehicle, there were still more events per mile in the leased vehicle than in the private vehicle. If there was an effect of adaptation, it was extinguished before the first week of driving was completed. In addition, drivers appeared to adapt to the presence of the unobtrusive instrumentation within the first hour of driving.

There is a strong possibility that AVs will encounter both aggressive driving and road rage, or simply poor driver behaviour. A relevant research question is: **how for example might an AV manage a situation in which another driver is being deliberately antagonistic, driving in a manner with the intention to harm the AV and/or its occupants, or simply driving with poor care and attention to the task of driving?**

2.6 Summary

The preservation of gaps between consecutive vehicles in a system is critical to avoiding collisions. Based on drive on sight systems, the creation and preservation of appropriate gaps is in the gift of the driver. In links these gaps may be eroded by following vehicles and this may necessitate additional gaps being offered by a vehicle that is being followed too closely in order to mitigate the effect. At junctions, drivers will accept gaps in order to make manoeuvres. The acceptance of a gap will result from a decision about the value of accepting the gap relative to the potential risk. This is a rather different mechanism than the one that ought to be acceptable for AVs, which will be based on minimising risk alone. The approach to human decision making in a complex system such as a road environment may stray well beyond bounds of rationality and emotional response to situations may create rather violent reactions manifest as 'road rage'. AVs will behave more predictably and their presence in the mix of other road users will therefore introduce an additional degree of control. This may have general beneficial effects in reducing driver error, so long as countervailing human emotional responses do not dominate.

3 Interactions between vehicles and bicycles

3.1 Introduction

Cycling plays an important role in the transport function in many countries, particularly in urban areas, and is growing in importance in a number of UK towns and cities. Goodman (2013) shows that cycling to work increased by 0.1% to 3.1% in the decade to the 2011 census. At a regional level the change in level of cycling was in the range -0.6% to +0.2%, with some marked increases at the local level; for example, Cambridge +4.2% to 32.6%, Oxford +2.8% to 19.1%, London Borough of Hackney +8.5% to 15.4% and Bristol +3.3% to 8.2%.

There have been a number of initiatives encourage cycling in the last decade. Notably, the six Cycling Demonstration Towns (2005 to 2011) and the twelve Cycling Cities and Towns (2008 to 2011) in England were provided with capital for infrastructure improvement and revenue for promotion and training. Goodman

analysed the commute to work of the 1.3 million commuters in the 18 intervention towns and found an increase significant at the 95% level of confidence of 0.69% to 6.8% in 2011.

Questions remain, however, about the nature of the interventions which encourage cycling. This section of the literature relating to cycling begins with a general review of issues in relation to the built environment and motivators related to cycling (Section 3.2) before then turning its attention to cycling safety in the generality and to consider which factors are relevant to interactions with autonomous vehicles (Section 3.3). The main section within this part of the literature review is Section 3.4 and this discusses interactions on links and at junctions. There is a final section which introduces the literature available on AVs and cyclist interactions in Section 3.5.

3.2 The built environment and behavioural motivators

Fraser and Lock (2010) sought to discover whether active transport strategies, which modify the built environment, have impact on physical activity and cycling in particular. The method consisted of a systematic literature review of experimental or observational studies that objectively evaluated the effect of the built environment on cycling. A total of 21 studies met the inclusion criteria, all of which were observational studies. These studies identified objectively-measured environmental factors with a significant positive association with cycling: presence of dedicated cycle routes or paths, separation of cycling from other traffic, high population density, short trip distance, proximity of a cycle path or green space and, for children, projects promoting 'safe routes to school'. Negative environmental factors included: perceived and objective traffic danger, long trip distance, steep inclines and distance from cycle paths. Of the seven studies which focused primarily on the impact of cycle routes, four demonstrated a statistically significant positive association.

Fraser and Lock note that many types of environmental policies and interventions have yet to be rigorously evaluated. It is unsurprising that both perceived and objective traffic danger are environmental factors which have a negative association with cycling, and the question remains open as to the impact that autonomous vehicles may have on these perceptions or in actuality.

In a survey of 1,402 current and potential cyclists in Metro Vancouver, 73 motivators and deterrents of cycling were evaluated (Winters *et al.* 2011). The top motivators, consistent among regular, frequent, occasional and potential cyclists, were: routes away from traffic noise and pollution; routes with beautiful scenery; and paths separated from traffic. The top deterrents were: ice and snow; streets with a lot of traffic; streets with glass/debris; streets with high speed traffic; and risk from motorists. In factor analysis, the 73 motivators were grouped into 15 factors. The following factors had the most influence on likelihood of cycling: safety; ease of cycling; weather conditions; route conditions; and interactions with motor vehicles. While these findings are based on behavioural intent rather than actual behaviour, they do indicate the importance of the location and design of bicycle routes to promote cycling.

Dill and McNeil (2013) examined the validity of a typology developed by the City of Portland, Oregon, that categorised cyclists into four groups regardless of their current cycling behaviour: 'the strong and the fearless,' 'the enthused and confident,' 'the interested but concerned,' and 'no way, no how'. The study, based on a random phone survey of adults in the Portland region, placed respondents ($n = 908$) into one of the four categories on the basis of how comfortable they felt cycling on a variety of facility types, their interest in cycling as a transport mode, and their physical ability to cycle. Nearly the entire sample fit clearly into one of the four categories.

A majority (56%) of the sample fitted in the 'interested but concerned' category: considered the key target market to increase the use of cycling as a form of transport. A reduction in traffic speed and an increase in the separation between bicycles and motor vehicles (e.g. cycle paths) might increase levels of comfort and

cycling rates for this category. General concern about the amount of traffic and traffic speeds in neighbourhoods, along with a lack of cycle lanes and destinations nearby, appeared to prevent ‘interested but concerned’ adults from cycling. Measures such as traffic speed controls, traffic calming, and planning oriented to mixed land use could help overcome these barriers, in addition to bicycle-specific infrastructure.

Women and older adults (55+ years of age) were under-represented among the more confident and those who currently cycled for transport, and both were most likely to be in the ‘no way, no how’ category or else to be non-cyclists in the ‘enthused and confident’ and the ‘interested but concerned’ categories. Other research (such as Garrard *et al.* 2012) has indicated that common barriers for women include concerns about traffic, different attitudes toward cycling, and complex travel patterns, including the transport of passengers. Physical inability to ride a bicycle contributes to the large share in the ‘no way, no how’ category among older respondents. Non-traditional bicycle technologies, including electric-assist bicycles (e-bikes) and adult tricycles, might help overcome this barrier.

Social influence seemed relevant in influencing whether an ‘interested but concerned’ adult cycled for transport purposes as opposed to leisure, with those that did not cycle being less likely to live or work with people that cycled for transport, or less likely to see people that looked like themselves on bicycles on city streets.

A correlation was found between the experience of cycling to school as a child and the level of comfort with cycling as an adult. The ‘enthused and confident’ adults were most likely to have cycled frequently to school as children, while most in the ‘no way, no how’ group said that they never rode to school as children. Importantly, whether a person within any of the categories had cycled to school did not appear to influence the likelihood to currently cycle for transport or recreation. Because cycling frequency did vary by category, however, these findings support the hypothesis that increased cycling to school could have longer-lasting effects on overall rates of cycling.

Time constraints were an important barrier to cycling for transport among the ‘interested but concerned’. These could be addressed by land use and street patterns that shortened travel distances between destinations, as well as more direct cycle infrastructure. E-bikes might also be a solution for some adults.

Although self-reported knowledge of safe cycling practices in traffic was high, with more than 80% among the ‘interested but concerned’, a majority of all subgroups indicated an interest in learning more. It is unclear how much cycling education efforts would change levels of cycling. ‘Interested but concerned’ adults that did not cycle felt considerably less comfortable with the idea of cycling in the rain or in the dark.

Overall, we can see that, while there are complex and multi-factorial reasons why people may or may not cycle, there are significant groups of people who may be able to take advantage of the benefits of cycling if their perceptions of, and the realities of the hazards posed by motorised traffic can be ameliorated. An appropriate research question to ask is: **will assist, in the generality, in changing the perceptions of hazard posed by motorised traffic to cycle users?**

3.3 Cycling and risk from motorised traffic: the general issues

3.3.1 Human decisions within an infrastructure

Evidence from a review of the Dutch grey and academic literature (Twisk *et al.* 2015), including studies considering road users as well as infrastructure and vehicle measures related to cycling safety, found the following interventions to be important for better cycling safety: 1) area wide traffic calming; 2) roundabouts; 3) physically separated bicycle tracks; and 4) vehicle measures such as bicycle reflectors and truck side under ride protection.

The design of roundabouts can be quite different in different countries and in different circumstances. A so-called ‘English’ roundabout has flared approaches, wide circulating carriageways, acute entry angles and generous entry and exit radii allowing for ‘easy exits’. Compact (sometimes called continental) roundabouts may have one entry lane, one circulating lane, orthogonal entries and exits and tight radii. Roundabouts can hence be designed either as high capacity and high-speed junctions, or as junctions that assist in traffic calming while at the same time allowing for inter-connection between different links in the network. The research on roundabouts relating to cycling may therefore – depending on the nature of the roundabout and its country of location – be found to decrease rather than increase cycling safety (Hels and Orozova-Bekkevold, 2007; Daniels *et al.*, 2009).

Herslund and Jørgensen (2003) found that drivers entering a roundabout demonstrated a larger critical gap (the time gap below which 50% of drivers would not enter the roundabout) for cars approaching around the roundabout (4.26 seconds) as compared with the situation when cyclists were approaching on the roundabout (3.33 seconds). The critical gap provided to cyclists when both cars and cycles were approaching was 4.70 seconds, but the critical gap given to approaching cars did not change significantly. The authors suggest that therefore cyclists are not overlooked at roundabouts based on the presence of other cars. It should be noted that these observations were made on Danish roundabouts and the authors conclude that if cyclists ride in between cars then bicycles are located where approaching car drivers search for other vehicles and this may reduce the risk of a driver not seeing a cyclist.

Among the future challenges for cycling policy, Twisk *et al.* (2015) identify the increasing prevalence of older cyclists as the population ages. Younger and older cyclists have been shown to be more vulnerable than other age groups, but for different reasons and with different consequences. Young cyclists experience a high frequency of collisions with motorised traffic, whereas for the elderly the problem lies with their frailty combined with a high frequency of single-bicycle crashes. Whilst collisions with motorised vehicles are responsible for the large majority of cyclist fatalities, single-bicycle crashes, i.e. falls and collisions with obstacles, are mostly responsible for serious and minor cyclist injuries, and are common in countries with high cycle modal share.

Another challenge is concerned with ensuring a safe interaction of cyclists with innovative types of vehicles, for example electric and/or hybrid vehicle and highly automated vehicles. Collisions between alternatively-powered vehicles, which may be much quieter than conventionally-fuelled vehicles especially at lower speeds, and cyclists and/or pedestrians, might be more frequent

A study that examined crash data in the US (Wu *et al.*, 2011), for example, found that the odds of a hybrid vehicle being in either a pedestrian or bicycle crash are greater, 35 percent and 57 percent respectively, than the odds of a vehicle with an internal combustion engine being in a similar crash. The explanation is that cyclists use their sense of hearing alongside their vision to detect the presence, location and direction of motorised traffic.

Increasingly, automated vehicles may behave differently from the way cyclists and pedestrians have learned to expect them to behave and this may lead to confusion, errors, fear and increasingly unsafe interactions. An important research question in respect of human understanding of the expectations of AV behaviour is: **how does the presence of AVs with differing levels of automation affect interactions and decisions made by cyclists?**

AVs, as they develop further, will begin to learn how to interact based on the recorded experiences the vehicles have had, and this machine learning will in some ways and to some extent parallel the way that humans have learned to interact on roads. This combination of machine and human learning and adaptation will co-evolve and the result will be revised ‘cultures’ and ‘practices’ in both the human and the machine. A

related research question concerning human understanding of AV behaviour is: **how will the evolution of machine learning and related human learning take place while maintaining safe interactions between vehicles and cyclists?**

3.3.2 Classifications of collision types

Walker (2007) states that a useful picture of how collisions between cyclists and vehicles happen is provided by large-scale collision data surveys that have been carried out in the United States by Cross and Fisher (1977), in New Zealand by Atkinson and Hurst (1983), and in the United Kingdom by Stone and Broughton (2003). Collisions at junctions are a significant proportion of all collisions. Cross and Fisher (1977) reported that bicyclist behaviours (such as manoeuvres that traverse the carriageway to undertake turns) and motorist behaviours (e.g. tailgating bicycles closely) play a part in overtaking collisions and rear-end collisions respectively. The relatively consistent findings across all the studies confirm that collisions with cars moving in the same direction as cyclists are particularly likely to lead to serious injury, although this is often the result of shunts from behind, as well as collisions during passing itself. The literature also distinguishes between same-direction collisions, e.g. when a cyclist moves out from the usual nearside position (to avoid a pothole for example) into the same path as may be used by a motor vehicle, and same-direction collisions which do not involve poor rider behaviour, e.g. when a cyclist who is travelling straight ahead is struck by a driver getting too close whilst passing.

So far as non-junction collisions are concerned, Pai (2011) developed a mixed multinomial model to predict the likelihood of a collision being of one of three types: striking a bicycle while overtaking, colliding into the rear of a cycle, or an occupant of a vehicle opening the door into the path of a passing cyclist. He found that buses and coaches as 'collision partners' were more likely in overtaking collisions (confirming previous studies), and that traversing manoeuvres by bicycles across the carriageway to make turning movements were associated with overtaking and rear-end collisions. A collision between a bicycle and a motorcycle is more likely to be a rear-end collision, and a collision between a bicycle and a taxi is more likely to be a door opening collision.

Where accidents occur on unlit roadways and in adverse weather conditions, they are more likely to be rear-end crashes, which corroborates previous evidence (e.g. Wood *et al.* 2009) that the bicycle's poor conspicuousness, aggravated during night time, can increase risks of being struck from behind. An interesting research question is as follows: **to what extent would AVs be able to detect a cyclist in the road ahead when light and weather conditions are adverse?**

Roads in built-up areas were associated with more door opening collisions. Door collisions were more likely to occur on cycle lanes and one-way streets. Training and education of cyclists and motorists, especially certain groups such as taxi drivers, could assist. A further research question is as follows: **What is the extent to which an AV, when not being driven, can remain what might be termed 'passively' safe by preventing passenger egress when it is not safe for the occupants or others in the vicinity, such as cyclists to do so?**

3.4 Link and Junction interactions

This section is divided into seven parts as follows. 3.4.1 deals with models of the acceptability of cycling within the road environment in its generality. The following two sections (3.4.2 to 3.4.3) deal with overtaking on links and road narrowings. Junction issues are dealt with in the following three sections as follows: turning movements and priorities (3.4.4), issues in approach queues (3.4.5), and signalling of intentions (3.4.6). Section 3.4.7 provides some background on possible legislative developments in relation to the bicycle as a vehicle.

3.4.1 Acceptability models of cycling on links

Harkey *et al.* (1997) in an evaluation of cycle facilities videoed 13 sites in Florida, which had a cycle lane, a paved hard shoulder, or a wide kerb lane (i.e. no cycle lane but wider inside lane) facility. Still pictures were also taken when a driver overtook a cyclist. These data were used to establish a model, a Bicycle Compatibility Index (Harkey *et al.* 1998), useful to planners and engineers to determine the suitability of a road for cycling. The main variables affecting the separation distance between the cyclist and the overtaking vehicle were: the facility type, vehicle presence in the adjacent lane, the presence of an open drainage gully, the number of lanes, the speed limit and the total width of the road. Significantly, where the facility was a wide lane adjacent to the kerb as opposed to a cycle lane, the mean separation distance increased. It was also noticed that cyclists tended to be closer to the kerb at these sites. The study also found that the extent to which a driver deviated on encountering a cyclist appeared to be dependent upon the area, rural or urban, with the deviation being greater in rural settings.

Parkin *et al.* (2007) extended previous work on the Bicycle Compatibility Index and estimated two models of perceived risk, based on non-linear least squares, and a model of acceptability, based on the logit model, for whole journeys based on responses from a sample of 144 commuters to video clips of routes and junctions. This study extended previous work on the perception of the risk of cycling by considering a whole journey, including junctions, and by covering a wide range of independent variables. These variables were based on twenty different route and junction types using a novel means of presentation based on video taken from a moving bicycle which clearly conveys the situations that cyclists might possibly experience.

The sample was drawn from employees of Bolton Metropolitan Borough Council, the University of Bolton and Bolton Royal Hospital between January and July 2002. Only respondents who were physically able to ride a bicycle took part in the survey and they were classified as “never cycle” (35.4%), “cycle on occasional holiday times and weekends” (38.9%) and “cycle between one and three times per month or at greater frequency” (25.7%).

The risk models quantified the effect of motor traffic volumes, demonstrated that roundabouts added more to perceived risk than traffic signal controlled junctions, and showed that right turn manoeuvres increased perceived risk.

In contrast to the views presented by Hopkinson and Wardman (1996) and Wardman *et al.* (1997, 2000), facilities for bicycle traffic along motor trafficked routes and at junctions were shown to have little effect on perceived risk and this brings into question the value of such facilities in promoting bicycle use. This might be explained by respondents considering the presence of facilities as pointing to the presence of a hazardous situation, but that the facilities have not overcome the perceived hazard. The implication is that the provision of facilities at a junction may have a counter-intuitive effect and suggest to potential cyclists that the junction is more risky than it might otherwise have been perceived to be. Other factors such as the two-way flows and the number of parked vehicles *en route* also influenced the perceived risk.

The acceptability model confirmed the effect of reduced perceived risk in traffic free conditions and the effects of signal-controlled junctions and right turns. The interesting question that possible introduction of AVs into the traffic stream raises is as follows: **how may perceived risk within a network be altered for cycle users by the presence of AVs in the vehicle stream?**

3.4.2 Overtaking distance and lane markings

Motor traffic passing a cyclist exerts a lateral force because of the air turbulence created (Parkin & Meyers 2010). The kinematic envelope⁸ of a bicycle is wider than its physical size, and a buffer zone beyond the kinematic envelope is needed for safety reasons and to limit the feelings of danger resulting from closely passing motor traffic moving at a different speed. The space recommended varies between countries (Allen *et al.*, 1998). The UK Highway Code (UK Government, 2013) indicates that drivers overtaking cyclists should leave at least the width of a car (Rule 163). The Federal Highway Administration suggest a tolerance limit is defined as 16N (3.5 lbs), equivalent to heavy goods vehicle traffic travelling at 50mph, which is 1.2m from the cyclist. This is a little less than the force experienced during normal service braking of cyclists.

Dutch design guidance (CROW, 1993) identified three categories of cross-section in relation to joint cycle and motor traffic use as follows: 'tight' cross-sections along which it is not possible for an overtaking manoeuvre to be made without encroaching into the oncoming traffic lane; 'spacious' cross-sections which provide for adequate passing distance without having to cross the centre-line; and 'critical' cross-sections (which include the typical lane width of 3.65m as adopted in the UK, for example). The critical cross-section provides sufficient width for drivers to overtake, but in so doing they will leave inadequate distance to the cycle user they are passing. The decision to overtake or not may be influenced by the driver's perception of the consequence of crossing a line marking, and whether oncoming vehicles are present (Goodridge, 2006; McHenry and Wallace, 1985).

The UK Traffic Signs Manual states a minimum cycle lane width of 1.5m (DfT, 2003) although the Manual for Streets recommends 2.0m (DfT, 2007). Cosma (2012) and Hunter *et al.* (2011) suggest that cycle lanes can provide reassurance for inexperienced cyclists and help to remind vehicle drivers that cyclists may be present.

Centre-line road markings have been used since 1914 (Debell, 2003). Some research suggests that speeds are reduced when centre-lines are removed (DfT, 2007; Debell, 2003; Kennedy *et al.*, 2005). Guidelines in the Traffic Signs Manual allow omission of the centre-line if rural roads are less than 5.5m wide (DfT, 2003), and this guidance demonstrates the way that custom and practice has developed whereby centre-line marking is the default approach. There is a lack of research on the safety of centre-line road markings, particularly in relation to vulnerable road users (Stewart & McHale 2014). An interesting question in relation to AVs and cyclists is: **Are AVs able to overtake cyclists both with and without centre line markings with no difference in the impact on cycle users perceptions of safety?**

Scholarly interest in studying interactions between motorists and cyclists during an overtaking manoeuvre dates back to the 1970s and explores various types of contexts in which the passing takes place and the effect of various features including the presence of cycle lanes. The current literature in the field of cycle lanes has often shown contradictory evidence as to the benefits and risks of cycle lanes and previous work has specifically shown that on higher speed roads, drivers may pass closer to a cyclist when a cycle lane is present (Stewart & McHale 2014).

Early research studies, for example, (Kroll and Ramey, 1977; McHenry and Wallace, 1985) found no change in passing distances with cycle lanes. Kroll & Ramey (1977) carried out a study involving the filming of several urban streets, both with and without cycle lanes, in California, United States of America. This was supplemented by data from three additional sites both prior and post construction of cycle lanes. The research consisted of photographically capturing interactions between cyclists and other road users in. This study found that on streets with bicycle lanes:

⁸ The cross-sectional envelope defined by a moving vehicle.

1. Drivers, when passing cyclists, exhibited decreased variability in the deflection distance from their travelled path, but these results were conclusive only for roads with speeds of 35 mph or less.
2. There was no change in the mean separation distance between bicycles and motor vehicles.
3. Car displacement decreased (drivers maintained a smaller separation distance).
4. Lateral dispersion of bicycles and motor vehicles travelling alone was narrowed.

More recent work has found slower overtaking speeds for road widths of 3.0–6.4m without a cycle lane (Wilkinson *et al.*, 1992), and (with the exception of Chuang *et al.*, 2013) that cycle lane markings reduce the passing distance given to a cyclist by motor vehicle drivers (Parkin and Meyers, 2010; Harkey and Stewart, 1997; Wilkinson *et al.*, 1992). However, Haileyesus *et al.* (2007) suggest that cycle lanes deliver a safety benefit.

Parkin and Meyers (2010) collected proximity data of motor traffic overtaking cycle traffic on roads with and without cycle lanes using an instrumented bicycle. Three sites in Lancashire (two rural and one urban) were selected for analysis and had posted speed limits of 30mph, 40mph and 50mph (48kph, 64kph and 80kph). The study reported the recorded Annual Average Daily Traffic (AADT) flows at the sites. All cycle lanes used in the experiment were advisory and uncoloured.

The results show that significantly wider passing distances are adopted by motorists in the condition without a 1.45m cycle lane, with posted speed limits of 40mph and 50 mph with a 9.5m wide carriageway. These findings were not replicated for a similar width road with a posted speed limit of 30mph and a 1.3m cycle lane. These results suggest that in the presence of a cycle lane, drivers may be driving within the confines of their own marked lane with less recognition being given to the need to provide a comfortable passing distance to cycle traffic in the adjacent cycle lane. The data do not support a view as to what a comfortable passing distance should be and this would require further research considering objective measures of comfort, such as lateral force and noise, as well as self-reported ratings of comfort.

Chuang *et al.* (2013) investigated how motorised vehicle-related factors (passing vehicle type and passing time), road-related factors (surface condition, lane separation, and slow traffic separation), and cyclist-related factors (gender and the mean and variance of the wheel angle and speed before motorists passed) influenced the motorists' initial passing distance. Additionally, the study considered how these factors influenced the cyclists' behaviours after the motorists started to pass, in respect to their position (measured by the lateral distance to the passing motorists), changes in direction (measured by the wheel angle), and changes in speed. A quasi-naturalistic riding method and a first-person perspective were used. Thirty-four (16 male and 18 female) cyclists, aged 19-26 and recruited from a university campus in Taiwan, participated in the study by riding an instrumented bicycle in their natural way on a planned route in real traffic. Generally, the male participants appeared to have more experience riding a bicycle and a motorcycle. The study included 1380 incidents of left-side passing by motorists.

Initial passing distance and mean lateral distances were smaller for motorcycles than for cars and light goods vehicles. The minimum distance was 34 cm. The cyclists had weaker lateral stability when they were passed by buses. In addition, a longer passing time caused the cyclists to adopt cautious but less stable riding behaviours. Of the passes with a passing time longer than 1.3 seconds, 30% were produced by motorcycles, 43% by cars, 15% by light goods vehicles, 6% by buses, and 6% by heavy goods vehicles.

Concerning road-related factors, the existence of a solid white line separating cyclists from motorised traffic was shown to have a positive effect on initial vehicle passing distance and allowed the cyclists to ride in a different path than the one used by motorists, maintaining a low speed and remaining stable. When cyclists avoided road surface hazards, they reduced the initial passing distances that the motorists had chosen.

Considering cyclist-related factors, the motorists allowed a greater initial passing distance for female cyclists. There were also gender differences related to the cyclists' lateral control, and differences in road use experience may explain this gender difference. Furthermore, the cyclists' wheel angle⁹, speed, and speed variation affected the motorists' initial passing distance. These results also revealed that cyclists perceive and respond to risk in distinctive ways under different road conditions.

In terms of the relationship between vehicle type and overtaking behaviour, Basford *et al.* (2002) found that professional drivers of smaller vehicles were more likely to take risks and to overtake, while Sando and Moses (2011) found that smaller vehicles left less overtaking space. Walker's study (2007) did not take account of available carriageway widths or the widths of the passing vehicles but nevertheless showed that longer vehicles, such as buses and heavy goods vehicles, tended to get closer on average when passing the bicycle, a finding replicated by Parkin and Meyers (2010) when cycling 0.5m from the kerb. When platoon driving was considered (defined as when vehicles are within 5s of each other) no difference in overtaking proximities for cyclist positions of 0.5–0.8m from kerb were found by Walker *et al.* (2013), although a tendency for the following driver to pass closer was observed. Long vehicles were particularly associated with bicycle overtaking collisions in a study using United Kingdom police accident records (Pai 2011) and in an equivalent study using American data (Kim *et al.* 2007). This can indirectly suggest that closer proximities measured on the road by Walker (2007) and Parkin and Meyers (2010) might indeed translate into real collisions (Pai, 2011). Chuang *et al.*'s (2013) finding of decreased rider stability during a lengthy overtake could explain one possible mechanism for this.

The proximity and speed of motor traffic passing cyclists in non-separated conditions may be so close and so great as to cause discomfort. To understand how a variety of road design and driver behaviour factors affect overtaking speeds and distances, Shackel & Parkin (2014) considered the presence of cycle lanes on 20mph and 30mph roads, different lane widths, different lane markings, vehicle type, vehicle platooning and oncoming traffic. Data were collected from a bicycle ridden a distance of one metre from the kerb fitted with an ultrasonic distance detector and forward and sideways facing cameras. Reduced overtaking speeds were shown to correlate with narrower lanes, lower speed limits, and the absence of centre-line markings. Drivers passed slower if driving a long vehicle, driving in a platoon, and when approaching vehicles in the opposing carriageway were within five seconds of the passing point. Increased passing distances were found where there were wider or dual lane roads, and in situations where oncoming vehicles were further away and not in a platoon. In mixed traffic conditions, cyclists will be better accommodated by wider cross-sections, lower speed limits and the removal of the centre-line marking.

Utilising an instrumented bicycle, Stewart & McHale (2014) collected data on overtaking speed and overtaking distance of vehicles in a range of circumstances, including the following: 20mph and 30mph speed limits; 'tight', 'critical' and 'spacious' widths; circumstances with a single lane, a cycle lane, two lanes, and a single lane with no centre-line. Vehicle types were noted, and whether or not oncoming vehicles were present was also recorded. A number of significant findings have emerged; some confirm previous results, while others are contradictory. For instance, users of roads with cycle lanes reacted more positively towards them when asked about them in qualitative studies; whilst in some cases drivers demonstrated 'more risky' behaviour (speeding and closer overtakes) at sites with cycle lanes when it came to quantitative data gathering. When a driver encounters a cyclist mid-block (i.e. not at a junction), there are more significant variables than the presence of a cycle lane that determines the overtaking distance.

The three most significant variables identified were: absolute road width, the presence of nearside parking and the presence of an opposing vehicle at the time of an overtaking manoeuvre. The analysis also

⁹ Angle of the front wheel relative to the frame

demonstrated that there is a larger unknown factor when it comes to overtaking distances, which Stewart & McHale (2014) suggest this may be the driver himself and will vary by area, site and even time of day (i.e. different driving cultures, congestion, or frustration during peak times, etc.).

The findings provide evidence for road design and management to better accommodate cyclists. Giving cyclists more road space has been and remains an issue in design guidance, for example UK Department of Transport guidance suggests providing 2m wide cycle lanes (DfT, 2008), and this is recommended by other researchers (Navin, 1994). The evidence presented by Stewart & McHale (2014) is inconclusive, however, on the effect of cycle lanes at posted speed limits of 20mph and 30mph. Cycle lanes have no beneficial effect on passing distances and speeds.

Chapman & Noyce (2012) collected real-time video and sensor data for 1,151 interactions between bicycles and motorised vehicles in south-western Dane County (South Central Wisconsin, US) along state and county trunk highways and local rural roads. This study found that:

1. Drivers operated in a technically unsafe manner by frequently performing passing manoeuvres outside of designated areas.
2. Despite the frequent comment from cyclists that drivers pass too closely, these actions were actually quite rare, at least for rural roads in the area around Madison, Wisconsin, accounting for only 0.5% of all the observed interactions (6 of 1,151). Drivers were far more likely to give cyclists more room than required, risking a centreline violation, even when conditions were not safe to do so.
3. As a group, the percentage of vehicle type and the percentage in violation for that vehicle type were approximately equal. Only pickup truck drivers were disproportionately likely to commit a moving violation.
4. Finally, cycle lanes (paved shoulders) directly affected the likelihood that a driver would commit a moving violation, with violation rates four to six times lower when a paved shoulder was available.

Walker (2007) used an ultrasonic distance sensor, mounted on a bicycle, to measure the space left by motorists as they overtook the bicycle in two United Kingdom cities (Bristol and Salisbury). This naturalistic experiment study showed the effects of the cyclist's lateral road position, helmet wearing and gender on the space left by passing vehicles. Drivers left less space (in the range 0.25–1.25 m) when the researcher rode towards the centre of the lane, in the morning peak hour than the evening peak hour, and when the rider was wearing a helmet. Instead, more room was given when the researcher wore a long wig so that he appeared to be a woman. Drivers also gave less room when overtaking a cyclist positioned further from the kerb. The results suggested that motorists may exhibit behavioural sensitivity to aspects of a cyclist's appearance and behaviour during an encounter.

Considering specifically the possible effects of the rider's appearance, Walker *et al.* (2014) studied whether drivers overtaking a bicyclist changed the proximities of their passes in response to the level of experience and skill signalled by the cyclist's appearance. Seven outfits were tested, ranging from a stereotypical sport rider's outfit, portraying high experience and skill, to a vest with 'novice cyclist' printed on the back, portraying low experience. A high-visibility bicycling jacket was also used, as were two commercially available safety vests, one featuring a prominent mention of the word 'police' and a warning that the rider was video-recording their journey, and one modelled after a police officer's jacket but with a letter changed so it read 'POLITE'. An ultrasonic distance sensor recorded the space left by vehicles passing the bicyclist on a regular commuting route in the South East of England. 5,690 data points were collected. The only outfit associated with a significant change in mean passing proximities was the police/video-recording jacket. Contrary to predictions, drivers treated the sports outfit and the 'novice cyclist' outfit equivalently, suggesting they do not adjust overtaking proximity as a function of a rider's perceived experience. Notably, whilst some outfits seemed to discourage motorists from passing within 1 m of the rider, approximately 1–2% of overtakes came

within 50 cm no matter which outfit was worn. This suggests there is little riders can do, by altering their appearance, to prevent the very closest overtakes; it is suggested that infrastructural, educational or legal measures are more promising for preventing drivers from passing extremely close to bicyclists. Fortunately, if properly programmed, these differences in passing distance should not be encountered when AVs pass cycle users.

The gender effect shown by Walker (2007) was later replicated in studies using real female riders by the Florida Department of Transportation (2011) and Chuang *et al.* (2013), in the United States and Taiwan respectively. Walker also found that vehicles passed closer the further out he cycled (Walker, 2006).

There remain questions about how an AV might be programmed to make decisions about overtaking cyclists. Rule 163 of the Highway Code instructs the driver as follows: ‘You should ...move quickly past the vehicle you are overtaking...’ and ‘...allow plenty of room...’ and ‘...give motorcyclists, cyclists and horse riders at least as much room as you would give when overtaking a car...’. Hence there is not specified overtaking distance. An important question therefore is: **For different speeds, what is an appropriate distance to be provided by an AV when overtaking a cyclist in order to provide a minimum level of comfort for the cyclist?**

3.4.3 Interactions at road narrowings

Road narrowings can be created by pedestrian refuges, central islands, pinch points, chicanes, build-outs and hatching and other carriageway markings. There has been increasing utilisation of such features as traffic calming measures within the UK, particularly since the introduction of the Traffic Calming Act 1992 and Highways (Traffic Calming) Regulations in 1993 (Gibbard *et al.* 2004). The majority of the current guidance concerning road narrowing features can be found in the Department for Transport’s Traffic Advisory Leaflets.

Gibbard *et al.* (2004) reported the results of a research study on Cyclists at Road Narrowings commissioned from TRL Limited by the Department for Transport. This was part of the UG171 Cycle Facilities and Engineering project, looking at the performance of several types of cycle facility. The research consisted of three main elements: 1. A consultation with cycle users to ascertain their views on road narrowing features and their experience of negotiating them in traffic. 2. Video surveys of sites where features were installed by highway authorities to assist cyclists in negotiating road narrowings. 3. Virtual reality simulations of encounters between drivers and cyclists, allowing the reactions of drivers to be accurately measured under a range of circumstances.

The consultation survey received a total of 393 responses and included 15.5% females and 84.5% males. The large majority of the responses were obtained from male cyclists aged between 30 and 50 who not only cycled frequently, but had done so for several years.

The study found negotiating road narrowings constituted a source of stress to cyclists (for 46.6% of the respondents). Although other road conditions were identified as being more stressful to cycle users, narrowings were nevertheless considered problematic, with 33.6% (more females than males) reporting they were intimidated by cars as they approached a road narrowing.

Among the features that made respondents feel the most stressed or vulnerable when cycling were: the need to travel around large roundabouts (36.4%), followed by high proportion of heavy vehicles (17.8%), turning right in traffic (12.2%) and fast traffic (11.2%). Conversely, among the conditions under which respondents felt most safe and confident when cycling were: slow traffic (46.3%), followed by traffic signals (14.5%) and road humps (10.9%). There was no significant variation in the type of response across age and gender but some variation dependent upon the frequency with which the respondent cycled.

When asked to indicate what most increased their concerns when cycling through road narrowings in the presence of another vehicle, respondents selected the following: if a vehicle passed them when moving

through the narrowing (39.2%); and if the vehicle looked or sounded as though it were moving fast (27.2%). More female than male participants stated that a vehicle passing at any distance whilst moving through a narrowing increased their concern. Similar proportions of males and females indicated that a vehicle sounding or looking as though it were moving fast increased their concerns (27.1% and 27.9% respectively).

The size of the vehicle also matters, with higher proportion of cyclists feeling intimidated or stressed by larger vehicles in a road narrowing. Conversely, smaller vehicles such as motorcycles appeared less stressful. The majority of respondents felt the presence of light vans (59.8%) and medium or heavy lorries (61.6%) made them feel intimidated or stressed when approaching a road narrowing, even those with more cycling experience. A greater proportion of female than male participants stated that they were intimidated by buses.

When large vehicles were present, some cyclists adopted various strategies, including riding on the footway and selecting alternative routes to avoid narrowing features. The cyclists who participated in the survey reported that they normally carried out certain actions such as looking behind, or making eye contact with drivers when they approached a road narrowing. However, most of the respondents indicated that they did not always carry out these actions, suggesting that familiarity and practice might encourage greater confidence and relaxation.

More than half (52.4%) always looked behind them on the approach to a road narrowing to check for other roads users, whilst a third usually did so. The distribution of responses to this question between female and male respondents was similar. 37.2% usually made eye contact with drivers as they approached a road narrowing, although a similar 31.6% only sometimes did so. 9.9 % of males compared to 3.3 % of females stated that they never made eye contact with drivers. Whilst 55.7% of males compared to 41% of females stated that they never pulled over, 52.5% of females compared to 39.2% of males sometimes pulled over. Overall, 30.5% sometimes moved into the centre of a lane to stop other vehicles from passing them at road narrowings, whilst 35.4% usually did so. 47.1% never moved onto the footway, whilst 46.8% sometimes did so. The use of eye contact at road narrowings by cycle users is a feature that needs to be researched in relation to autonomous vehicles. This mechanism will not be available. An interesting research question is: **how will cycle users negotiate road narrowings with AVs without the facility to use eye contact as part of negotiating the manoeuvre?**

Gender, age and frequency of cycling among respondents affected results in different ways. There was some indication that female respondents found negotiating road narrowings more stressful than their male counterparts. However, the relatively low proportion of female respondents made it difficult to reach firm conclusions about this. The age of the cyclists often seemed to have a bearing on the responses given, although the effect of age seemed contradictory across responses.

Concerning cycling frequency, those with greater amounts of regular cycling experience were less likely to pull over at a road narrowing, and felt more confident about moving into the centre of the lane when the road narrowed. They also appeared to be less cautious in their behaviour when approaching road narrowings.

Respondents noticed that many drivers accelerated to pass them before a road narrowing, and were unlikely to wait for them to clear the narrowing. However, the majority of the respondents indicated it was rare for drivers to sound their horn or 'rev' their engines when they encountered them at a road narrowing.

In sum, road narrowings were generally not sufficiently threatening to force cyclists to utilise the footway, or choose alternative routes for their journeys, but that these effects could occur in particular circumstances. This was also indicated by the fact that road narrowings did not feature especially highly as a feature that caused stress when cycling, and the majority of the respondents indicated that large roundabouts intimidated them the most. Nevertheless, while narrowings were considered relatively less stressful than some other situations, they appeared to have the capacity to cause anxiety and, at the extreme, behaviour

change, among cyclists. A higher proportion of respondents viewed road narrowings caused by traffic calming measures as more of a problem than those created by parked cars.

Road narrowings may reinforce the perception that parts of the highway network are inimical to cyclists and may contribute towards a reluctance to contemplate cycling among some members of the public. Where narrowing features are provided in order to calm traffic, Gibbard *et al.* (2004) recommend that they should not be installed where they lead to running widths of less than 4m, unless additional features to significantly reduce vehicle speeds are incorporated. They also recommend that where substandard width road narrowings are installed without speed reducing features, they should be closely monitored following installation. Even where road narrowings of 4 metres or above are installed, they may lead to difficulties for cyclists if they fail to reduce vehicle speeds.

Road narrowings, in some respects, may be said to work as traffic calming, with indications from this study that they may cause drivers to slow. When forced into close proximity to cyclists by features that narrow the roads, a significant proportion of vehicle drivers will brake. However, the survey results suggest that, even among experienced cyclists, this is likely to be at the cost of some stress to the cyclist. The calming effect of narrowings and the improved crossings for pedestrians are therefore achieved at a price to the cyclist in a significant proportion of cases.

The measures to assist cyclists at road narrowings were found to have limited benefit. This included some unexpected effects, such as appearing to encourage more risky behaviour among motorists, including passing closer to cyclists and attempting to overtake cyclists before the narrowing. The virtual reality testing found that, despite some gender differences in behaviour, central islands appeared to have a speed reducing effect on motor vehicles. The provision of a simple advisory cycle lane in conjunction with the traffic island appeared to have little significant effect on behaviour. A cycle lane with coloured surface was found to be more effective in promoting safer driving behaviour, reinforcing the finding from the video survey. Drivers recognised that cycling on the highway was not always pleasant and that narrowing features contributed to that.

The slowing of traffic speeds has potential to reduce actual and perceived risk to cyclists and it is recommended that cycle lanes introduced through road narrowings be given coloured surface treatment. Given the tendency of drivers to pass cyclists more closely where cycle lanes exist, Gibbard *et al.* (2004) recommends that the minimum recommended width of the cycle lane is 1.5m and, wherever possible, cycle lanes of 2m wide should be provided.

3.4.4 Turning movements and priorities

In Germany, the behaviour of road users during turn manoeuvres needs to comply with road traffic regulations (StVO), which state that a vehicle turning left or right must give way to cyclists cycling straight ahead. Schreiber *et al.* (2015) analysed collision data and made observations of traffic behaviour in Germany. Cycle tracks crossing side roads at a moderate or considerable set-back distance from the junction are problematic during a vehicle right turn (equivalent of the left turn in the UK). Sometimes this is exacerbated by obstructions to visibility that prevent or significantly reduce visual contact between motorists (on the carriageway) and cyclists (on the adjacent cycle track). At priority junctions it is the left turn into the side road (right turn in the UK) when cyclists are using the carriageway that are problematic. These types of collisions tend to be very severe despite not being the most frequent. When turning at junctions, whether or not there is other motor traffic in front of the turning vehicle, drivers need to be especially aware that cyclists may be approaching from behind and they may fall outside their field of vision. It is suggested that driver assistance systems may help prevent collisions between turning vehicles and cyclists, for example by detecting cyclists approaching from behind at high speed when the vehicle is making a turn at low speed;

and by detecting cyclists coming in the opposite direction of travel when the vehicle is making a left turn. A critically important question is: **How accurate are AVs in detecting cyclists who are making straight on manoeuvres at junctions across side roads either within the carriageway or on adjacent cycle tracks and what is the ability of the AV to come to a correct decision about its behaviour in relation to the cyclist or cyclists?**

75% of reported injury accidents to cyclists occur at junctions. In around 50% of the reported crashes at junctions, the cyclist is going straight ahead (Phil Jones Associates Ltd., 2016). Bikeability training teaches cyclists to protect themselves by taking up a primary position towards the centre of the carriageway when passing side roads to make themselves more visible to drivers and to prevent overtaking near the junction. This is not always possible on busy roads or in fast moving traffic. Moreover, painted cycle lanes and cycle tracks place cyclists right at the edge, making it difficult to be in a clear position within a driver's field of vision. The provision of more segregated infrastructure is welcome. However, designers and cyclists are concerned that the current laws do not offer adequate protection for cyclists travelling to the nearside of general traffic lanes (on the shared carriageway, in a painted cycle lane, or on a cycle track) who are at higher risk of collision with turning vehicles. Because of this risk, designers are often reluctant to create cycle tracks with priority across side roads, resulting in unattractive 'stop-start' facilities with no priority for cyclists, or expensive overly complicated solutions such as staggered toucan crossings. Consequently, many cyclists choose convenience over safety and remain on the carriageway where they have an uninterrupted right of way, even if a cycle track is provided. This undermines safety, thereby reducing the value of investment in cycling infrastructure.

The ambiguity about rights of way when turning is also problematic to pedestrians. This is especially the case for people with disabilities who need time to cross side roads, and for blind people who have must rely on drivers adhering to Rule 170 of the Highway Code. Britain is one of only four European countries without a 'Presumed Liability' that drivers are primarily responsible for collisions with pedestrians and cyclists unless proven to the contrary. Experts from continental Europe consulted by Phil Jones Associates Ltd (2016) considered that Presumed Liability was an important factor underpinning general driver behaviour around vulnerable users.

3.4.5 Issues in approach queues

Frings *et al.* (2014) extended the field of research relating to risk perception, attention allocation and behavioural intentions in the context of the approach to the end of a queue of traffic. The method involved tracking the eye movements of twenty cyclists viewing junction approaches presented on video, which included a variety of contexts: junctions featuring cycle lanes, large vs. small vehicles and differing kerb to vehicle distances. The study found that cyclists allocate around 60% of their attention to the nearside of vehicles they are approaching (side closest to kerb), and 40% to the offside (side furthest from kerb). Overall, cyclists considered near and offside passing as most risky. Waiting behind was the most frequent behavioural intention, followed by nearside and then offside passing. While cycle lane presence did not affect behaviour, it did lead to nearside passing being perceived as less risky, and to less attention being devoted to the offside. Wide kerb distances increased nearside passing intentions and lower associated perceptions of risk.

Large vehicles led to increased risk perceived with passing, and more attention directed towards the rear of vehicles, with reduced offside passing and increased intentions to remain behind the vehicle. Whether the vehicle was large or small, nearside passing was preferred around 30% of the time.

An interesting question: **will AVs be regarded any differently by cycle users in terms of where they allocate attention as they approach an AV in a queue with the intention of overtaking it, and will cyclists make**

different decisions about whether to overtake the AV or undertake it, and what will be cyclists perceptions of risk when they approach an AV when it is in a queue?

3.4.6 Signalling of intention at junctions

In three experiments Walker (2005) investigated drivers' responses when encountering cyclists at a T-junction. Twenty-five volunteers from the academic and administrative staff of a UK university took part in this study. They were aged between 19 and 58 (mean age 30) and all had normal or corrected-to-normal vision. The participants had been driving regularly for between 1 and 30 years (mean 10.32 years). In particular, a comparison was made between the cyclist indicating an upcoming turn with an arm signal, an informal signal of intent, or no signal. Overall, arm signals worked relatively well to inform drivers of the cyclist's intentions and were easier to perceive than informal signals. It was also found that simple failures to react to the cyclist in time were more common at shorter thinking times whereas incorrect positive responses were unaffected by thinking time. Arm signals often slowed down the participants' decision-making processes, leading to a lower probability of their stopping in time when the cyclist was at risk. The same was true for informal signals in which there was eye-contact between the cyclist and the participant. These effects may come about because both arm signals and eye-contact are communicative acts and therefore produce extra stages of involuntary cognitive processing in the drivers, thereby slowing their reactions. An interesting question in relation to AVs is: **what is the extent to which AVs are able to decipher cyclists arm signals accurately at junctions?**

An experiment tracked drivers' gaze patterns as they made judgements about the manoeuvring intentions of a cyclist at a T-junction (Walker & Brosnan 2007). The stimuli involved a factorial manipulation of the cyclist's arm-signals and gaze cues, as well as whether the participant viewed the bicyclist from the major road or the minor road. Overall, the data support the idea that participants were engaging in a form of socio-cognitive processing. There was a strong tendency for the face to be the very first part of the scene attended to, and this tendency was unaffected by the cyclist's depicted actions (his gaze and arm-signals) as well as by the participant characteristics of gender and experience. When the cyclist appeared in their view, drivers' attention tended to go straight to his face most of the time. This effect was particularly pronounced in situations where the cyclist was effectively making eye-contact with the participant. This bias may help explain slow driver decision responses to cyclists seen in previous studies (Walker, 2005). The driver participants in this experiment were apparently unaware of any attentional bias they exhibited.

3.4.7 Pedal cycle legislation

A wide range of pedal cycle legislation is currently enforced in Great Britain, covering construction standards, point-of-sale requirements and in-use issues (Robinson & Scoon 2013). Some of this legislation is specific to pedal cycles (or just bicycles) or electrically assisted pedal cycles (EAPCs), while others are more general but contain pedal cycles within their scope (e.g. the General Product Safety Regulations and Vehicle Lighting Regulations). Much of the existing legislation, however, was originally developed 20-30 years ago and may not adequately reflect more recent developments in cycle use, consumer markets or in technology. There are also some potentially confusing anomalies and/or inconsistencies between individual pieces of legislation, e.g. with some differences between requirements for cycles at the point of sale and when in-use on public roads.

The Department for Transport is subject to a wide range of policy pressures, all having the potential both to conflict with and complement each other. Particularly significant are the pressures to reduce legislative burdens while maintaining or improving safety levels. Robinson and Scoon (2013) conducted a study that gathered, generated and expert-reviewed evidence from a wide variety of sources on the forces and pressures influencing pedal cycle construction, sale and use in Great Britain, and provided costed, practical

and appropriate options for legislative change. The methodology included reviews of published research literature, Red Tape Challenge responses, previous consultation responses, existing legislation, and of cycle accident data held within the STATS19 database, combined with comprehensive consultation with stakeholders from the cycle industry, cycling groups, local authorities, operators, professional bodies, road safety organisations and enforcement agencies.

The reviews and stakeholder discussions led to the development of the following major options for legislative change:

Option A – Do Nothing (retain all UK regulations in their current form)

Option B – EAPC harmonisation & Brakes simplifications. This involves:

- Removing weight limits for EAPCs;
- Harmonising EAPC maximum power and assisted speed with EU at 250 W & 25 km/h respectively;
- Continuing to classify as pedal cycles, subject to type approval, those EAPCs, with twist and go, that meet 250 W max output and 25 km/h power cut-off;
- Removing voltage marking requirement from the EAPC data plate;
- Allowing 2,3 or 4 wheeled EAPCs;
- Keeping handed brake levers but allow suppliers to swap left and right hand brakes if customer requests it;

Option C – as B + Lighting simplifications, involving:

- Removing all references to British (lighting) Standards, relying on manufacturer and consumer choice to ensure lights and reflectors give adequate performance;
- As a minimum requirement, fitting front and rear light and rear reflector if the cycle is used at night, aimed to avoid dazzle or discomfort, properly maintained, etc.
- Option D – as C + Reflector simplifications, involving:
 - Removing requirement for pedal reflectors to be fitted at point of sale and in-use;
 - Removing requirement for rear reflectors to be wide-angle type;
 - Removing requirement for side and front reflectors to be fitted at point of sale.

The options for bells are:

- X - keep the existing requirements (for a bell at point of sale);
- Y – simplify by allowing audible warning device as alternative at point of sale (subject to performance requirements);
- Z - de-regulate by removing requirements for a bell.

A formal impact assessment, carried out in accordance with the Better Regulation guidelines, has provided estimates of the net present value of the benefits of the various regulatory options over the period 2015-2024, most of which stem from encouraging the EAPC and goods-delivery markets, with a small additional potential benefit from simplification of the reflector requirements.

The overall NPV of benefits for EAPC harmonisation and simplification of the braking requirements is estimated to be in the range £551 million to £1,191 million (central estimate £871m) at current prices over the ten year evaluation period (all of which comes from the EAPC changes alone), while simplifying the reflector requirements might take the overall maximum NPV up to £1,274 million (central estimate £912m).

Simplifying the lighting and braking requirements, and options for changes to the requirement affecting bells were found, on their own, unlikely to have any net overall cost or benefit.

Over the ten-year period to 2024, with 2014 as the base year and using a discount rate of 3.5%, these savings would be shared amongst:

- consumers (through car operating cost savings and health benefits), £0.42- £0.95 billion;
- businesses (through congestion cost savings, point of sale savings and goods- delivery/van operational savings), £0.13 - £0.32 billion and;
- the environment (through greenhouse gas reductions), £4 - £8 million.

Allowing for the various uncertainties in the assumptions made to generate these savings estimates, the overall benefits range could be somewhere in the range £0.40 - £1.63 billion. The most significant influence on the overall savings estimate is the assumptions regarding EAPC sales growth, and particularly the difference in that sales growth that might result from the Option B implementation (harmonisation).

Phil Jones Associates Ltd (2016) makes a number of recommendations for changes to the law. The Highway Code is revised approximately every ten years to take account of new signs, markings and other legislation and was last revised in 2007. Recent changes to the Traffic Signs and General Directions may prompt a revision of the Highway Code, offering an opportunity to strengthen protection for pedestrians and cyclists.

One option is to strengthen Highway Code Rules on Give Way to specifically include cyclists and cycle facilities. Changes to the Highway Code are expected to influence on drivers' behaviour over time, not only through new driver training but also by establishing a basis for assessing whether drivers are guilty of careless/dangerous driving offences by better defining what is considered reasonable and safe driving around cyclists and pedestrians at side roads. However, it would not introduce a direct offence.

Another option is to adopt Give-Way (or Diagram 1010 markings) as the marking of cycle tracks across side roads. This would require a revision of the regulations pertaining to the markings within TSRGD to make them enforceable under existing Section 36 of the Highways Act which requires drivers to obey traffic signals, signs and markings. Give-Way markings are universally understood and the same half-size marking is also used on cycle tracks. Using the give-way on entry as well as exit lanes of a side road with a priority crossing would be similar to the Netherlands. On-carriageway cycle lanes have the same status as bus lanes and there is already a requirement to give-way to cyclists when turning across them (stated in the Highway Code) although this is not widely observed or understood. The use of these markings would establish an enforceable requirement to yield on turning, and would complement the relaxation for cycle track crossings to be on a road hump in the 2016 TSRGD. No new primary legislation would be required. There are disadvantages in requiring road markings, for example due to visual impact. Recently completed sections of Cycle Superhighway 5 in south London have incorporated Diagram 1010 markings where side road entries cross the cycle track and appear to be well observed.

A third option is to adopt a 'Universal Duty to Give Way' to cyclists when turning, whether on a marked facility or not, which would be a new law as a section within the Highways Act. It would essentially embody the current advice in Rule 206 of the Highway Code but extend it to include cyclists on the carriageway. It would build on the existing accepted driver behaviour where a vehicle travels over a footway crossover and pedestrians enjoy priority. One advantage of a universal law is that it would reduce the requirement for additional give way markings at every minor side street, thus reducing street clutter associated with cycle facilities, and it would offer both pedestrians and cyclists greater legal protection when crossing. For all road users, a universal law offers clarity about expected behaviours compared to the wide variety of situations and differing priorities that occur at present. This would simplify enforcement and ease understanding and compliance.

A final option is to ratify the 1968 Vienna Convention for traffic signals to permit crossing movements at the same time as turns into a side road, supported by the universal duty to give way as above. Permitting traffic

turning into a side road to be released at the same time as pedestrians crossing the side road would reduce delays to all users. Pedestrians and cyclists would get longer crossing times, while turning vehicles would only be delayed when a pedestrian or cyclist is present, not at every phase of the lights. This would also reduce the requirement for shared footways or separate signal phases for cyclists at junctions where cyclists are permitted to make turns that are banned to other vehicles because cyclists could remain on the carriageway or separate cycle track. The signalling arrangements would bring the UK into line with other European nations and would bring greater consistency in traffic behaviour at signalised and non-signalised junctions, leading to safety benefits over time. Deaf and blind people would not be disadvantaged providing the universal duty to give way applies, although at present they have the additional benefit of fully separate signals in the UK.

Suggestions about changes in law are a reminder that an AV would not only need to be able to navigate within the existing infrastructure and rules of the road but also within any future changes in rules, some of which may be introduced specifically with AVs in mind, while other changes may pose greater challenges to AV use.

A potential research question is as follows: **what legislative changes might be particularly appropriate or helpful in the context of managing AV interactions with other road users?**

3.5 Interactions with AVs

Modelling the behaviour of AVs almost always ignores the presence of and interaction with cyclists and pedestrians. For example, the MITs Senseable City Lab project DriveWAVE produced a video of how an urban intersection might operate in a world of driverless cars. However, this does not show any pedestrians or cyclists (Jaffe, 2015).

Blau (2015) claims that most of the existing literature addresses interactions from the point of view of AVs as opposed to that of non-motorised users. The questions that need addressing include: **what roles will cyclists and pedestrians have in a driverless society? How will the presence of driverless vehicles change pedestrians' and cyclists' facility preferences and behaviour?**

His literature review of cyclists' perceptions of and preferences for different types of infrastructure reveals that, despite some disagreement, most sources claim that riders prefer segregated facilities. Fear of motorised traffic is also a major deterrent and certain key factors, namely motorised traffic speed, volume and street width, have been consistently shown to influence cyclists' and pedestrians' preferences and behaviours. Blau (2015) suggest that these road traffic features can change, albeit in different ways for urban and arterial roads. Declining levels of personal car ownership and increased levels of car/lift sharing services, coupled with automation, could contribute to less congestion and lower speeds in urban areas, while potentially higher speeds could be found in motorways. AVs would also require less road space and they would make more efficient use of the available road space, which could lead to increased space available for allocation to pedestrians and cyclists.

A web-based stated-preference survey administered by Blau (2015) asked respondents (n= 1,312) to select their preferred facility (wide shoulder, bike lane with and without buffer, and segregated cycle track) in various scenarios, with and without the presence of driverless vehicles, on-street types of varying motorized traffic volumes and speeds and different types of intersections. Three types of roads were considered: Street Type 1 was a quiet, two lane residential street with slow traffic and few vehicle; Street Type 2 was a moderately busy, three to four lane avenue with a mix of local and through-traffic, and speeds under 35 mph; Street Type 3 was a major boulevard with more than four lanes and lots of traffic travelling over 35mph. An ordered logit model showed that street type had a very strong influence on cyclists' preferences for more separated facilities as traffic volume and speed increased. Preference for separated bicycle facilities grows with increased motorized traffic speed, volume, and street width. Preference for protected, horizontally

separated facilities increases with each Street Type in current conditions (i.e. with no AVs), and preferences for protected, horizontally and vertically separated facilities increases with each Street Type in driverless vehicle conditions. This trend was more amplified for female than male respondents, and less amplified for those with prior knowledge of AVs and those with more cycling experience. Signalized intersection, separate lanes and universal Automated Intersection Management (capable of detecting vehicles as well as non-motorised road users) are the most preferred facilities when AVs are introduced, coming in second and first, respectively, for both Street Types 2 and 3.

An essay by Prof John Adams, UCL, (Adams, 2015) examines how current visions of a driverless future neglect to take full account of pedestrians and cyclists and focus on vehicle to vehicle interactions controlled by an algorithm. But these descriptions and demonstrations also stress that in the case of interactions between AVs and people (pedestrians and cyclists) the cars will have to be programmed to behave ‘deferentially’. According to Adams, this could lead to AVs spending their time ‘going nowhere’, suggesting that AVs may not be a very efficient transport mode in urban environments.

This was exemplified by a chance encounter between a Google driverless vehicle and a cyclist (Lewis, 2015) during a test drive on a public road in Austin, Texas. Although the car had arrived first at the intersection and had right of way, it was tricked by the track stand manoeuvre executed by the cyclist while he waited for the AV to go, and was unable to move from the intersection for a whole two minutes.

This reminds us that the variety and complexity of human behaviours that AVs will need to understand is very broad and very subtle.

3.6 Summary

Many of the issues in relation to the interaction of AVs with non-autonomous motor vehicles are similar for the interactions between AVs and cyclists. However, the interactions are brought into a sharper relief because of the more severe consequences of a collision occurring. In addition to, there is a wider range of complication concerning the interactions which relate to the ability of AVs to properly detect cyclists and detect their intentions via, for example arm signals. It is possible, but by no means certain, the road environment may become more comfortable for cycle users as a result of the presence of AVs within the vehicle mix as a result of greater compliance with the rules of the road. However, in some cases these rules of the road, for example overtaking distances to be offered by an overtaking vehicle, are presently rather vague. There are some possible significant additional advantages from the presence of AVs for example in remaining passively safe when not being driven by not allowing passengers to open doors when cars are parked in the road when a cyclists is overtaking.

4 Interactions between vehicles and pedestrians

4.1 Introduction

How ‘street’ or ‘road’ space has been used, perceived and hence designed has changed over the course of history in response to new mobility technologies (trams, bicycles, motorcars). Following each transition, a new set of rules and societal norms emerges which govern how pedestrians are expected and are able to negotiate the built environment. The potential transition to autonomous vehicles (AVs) will be no exception.

The purpose of this part of the review is to examine evidence on how pedestrians interact with vehicular traffic. It is intended to provide insights into the functional requirements of AVs in replicating human behaviour at potential conflict points with pedestrians. In setting the context for the review, the report first briefly summarises how pedestrian priority has changed since the beginning of the 20th Century and considers how the approach to planning transport networks has evolved. Section three then reviews studies of how pedestrians currently interact with motor vehicles in different contexts (along links and at crossing points). The final section summarises the sorts of ‘pedestrian protection systems’ that are currently being

developed for conventional cars, and considers some early stage designs for systems that would allow AVs to communicate with pedestrians in complex environments.

4.1.1 Historical context: Changing pedestrian priority

Before mass motorisation, streets were seen as places of social exchange in which the pedestrian had priority - apart from along the busiest thoroughfares perhaps, which during the early days of industrialisation, would be traversed by horse-drawn and later electric trams and bicycles. Even along these busier routes, there was little need for complex systems of traffic management and control, given the limited number and speeds of vehicles, and pedestrians remained relatively free to negotiate road crossings at their will.

This position of pedestrian priority remained in the early days of the private motor car. Indeed, a public backlash against the motor industry emerged in the US in the 1920s in response to the increasing numbers of pedestrians that were being killed or seriously injured by motor cars. Politicians were urged to introduce laws, not to restrict pedestrian movements, but to reduce vehicle speeds. This backlash against the motor industry has been suggested to have been significant enough to have contributed to a dip in US vehicle sales between 1923 and 1924, which had otherwise been steadily rising.

The response of the motor industry and their powerful lobby groups was robust and effective. By contrast, they sought to characterise pedestrians as the irresponsible party in the battle for road space. The term 'jaywalking'¹⁰ was coined successfully, to describe the act of crossing the road without due care and attention and pedestrians were encouraged to only cross roads at street corners (Thompson 2014). This marked the beginnings of a process of diminishing priority for pedestrians over the course of the 20th Century, both in the planning of transport networks and in their regulation. The notion that pedestrians should give way to the motor car became established as an accepted societal norm and to some extent reflected in law. Indeed, jaywalking later became (and remains) a criminal offence in America.

4.1.2 The planning of transport networks

The prospect of mass motorisation had far reaching implications for how urban areas and transport networks needed to be planned. As early as 1929, the French architect Le Corbusier, argued for the development of multi-level road networks to be imposed on ancient European cities. In the following quote (cited in (Fyfe 1998)), Le Corbusier exaggerates the problems associated with mixed use, polluted streets:

"It is the street of the pedestrian of a thousand years ago, it is a relic of the centuries: it is a non-functioning, an obsolete organ. The street wears us out. It is altogether disgusting! Why then does it still exist"

4.1.3 Buchanan's solution: Road hierarchies

The UK Government commissioned Colin Buchanan to examine the problem of accommodating large numbers of private cars in urban areas. In the seminal 'Traffic in Towns' report (Buchanan 1963), Buchanan proposed the development of hierarchical road networks based around two types of road i. *distributor roads*, designed primarily for the movement of private cars and ii. lower capacity *access roads* to serve buildings. Buildings were situated conceptually, within *environmental areas* which would be protected from large volumes of fast moving through traffic.

The overarching principle of this hierarchical approach was to separate traffic according to both the type of movement (e.g. fast moving through traffic versus slow moving access traffic) and the transport mode. The needs of pedestrians were thus considered to be best accommodated by segregating them (potentially by grade separation) from vehicular traffic. Hence, under this approach to network planning, pedestrian interactions with vehicular traffic would be minimised through design, as depicted in Figure 4:

¹⁰ Thompson (2014) suggest that 'jay' refers to a "derisive term for a country bumpkin"



Figure 4: Visions of a hierarchical transport network (Buchanan, 1963, p. 142, Figure 186)

4.1.4 Unintended consequences

The Traffic in Towns report (Buchanan 1963) was highly influential through the second half of the 20th Century, with many local highway authorities adopting functional road hierarchies in the planning of their road networks. However, the approach has been criticised in recent years. Marshall (2005) argued that functional road hierarchies have often failed (in their application rather than as conceived by Buchanan), to adequately cater for pedestrians and users of public transport. Hamilton-Baillie and Jones (2005) identified that the separation of vehicular traffic and social space, whilst well intended, could have the effect of cutting off residential or central urban areas when surrounded by arterial roads. These areas can be difficult to navigate on foot if access roads and district distributors are poorly connected. Segregation also limits the amount of space available for outdoor activity and produces poor quality public spaces or streets, which at the extreme may either become deserted at certain times of day (e.g. shopping precincts at night) or be dominated by vehicular traffic.

4.1.5 Alternative approaches

Hence, best practice now advocates the application of 'movement and place' hierarchies to assist with the sensitive design of transport networks. These seek to avoid the over prioritisation of movement at the expense of 'place making'. Manual for Streets published in 2007 (DfT 2007) provides guidance on how to plan walkable (permeable) residential neighbourhoods. It advocates the use of 'implicit design' techniques to reduce the dominance of vehicular traffic e.g. by limiting road widths, employing smaller turning radii at priority junctions and using sensitive landscaping. Such techniques reduce the need for the street furniture required for traditional traffic management and control techniques (e.g. signage, speed control humps) which can create cluttered environments. They also have the effect of equalising pedestrian and vehicle priority over road space and limit (rather than expect) segregation. At the extreme end of spectrum is the use of 'Shared Space', where there is no demarcation between pedestrian and vehicular spaces. In such contexts, pedestrian and vehicular movement is uncontrolled and it is left to the users to negotiate right of way. In comparison to the functional hierarchy approach, such principles require higher levels of interaction between pedestrians and vehicles.

4.1.6 The Highway Code

It is lastly relevant to briefly summarise the UK Highway Code (DfT 2016), which sets out a protocol for how to use the road. Many of the rules are backed by law. The 'Rules for Pedestrians' (extracts provided as Appendix A) characterise 'the road' as a hostile environment for pedestrians, in which motor vehicles are

expected to have priority. There are two circumstances under which pedestrians have priority over motor vehicles. These are: 1) when using a zebra crossing (motor vehicles are expected to slow down on approaches to zebra crossings, but pedestrians do not have priority until they have started crossing), and 2) when crossing a side road, a circumstance in which crossing (as opposed to waiting) pedestrians have priority over turning vehicles.

In contrast perhaps to the approaches set out in recent design guidance, the Highway Code advises pedestrians to navigate the built environment using and abiding by the traffic management measures that are provided for them (e.g. pavements, dedicated crossings, barriers). They are advised against following their own desire lines (e.g. do not cross diagonally across the road, do not cross between barriers). Hence this increases the importance of designing / engineering road networks that are sensitive to pedestrian needs. To date, there is no guidance for either motorists or pedestrians on how to interact in shared spaces.

4.1.7 Summary

The philosophy of network planning has moved from advocacy of pedestrian segregation at the beginning of the age of the motor car, towards the use of space sharing techniques in urban areas. Such modern 'Shared Space' approaches require and increase the number and complexity of interactions between pedestrians and vehicles.

The current UK Highway Code (DfT 2016) advises pedestrians to yield to motorists in most circumstances and to abide by the traffic management measures provided for them. Underlying these rules is the notion that interactions between users of the transport network are predominantly controlled through traffic engineering and regulation, rather than through on-road negotiations between users.

How planning thought and regulations will respond to the incorporation of AVs into the transport system is unknown at this stage. The level of physical segregation and changing codes of practice for how to use the transport system, will ultimately govern how AVs will be required to interact with pedestrians.

Thus the relevant research question so far as AVs is concerned is: **how ought the Highway Code to be adapted to provide guidance to pedestrians (and other road users) on how to negotiate right of way with autonomous vehicles?**

4.2 Pedestrian interactions with vehicular traffic

The review of pedestrian and AV interactions now turns to examine evidence on how pedestrians currently interact with vehicular traffic in different contexts (which are summarised in Table 3). Two broad themes are considered: firstly, pedestrian movement and vehicle interactions along links and secondly, pedestrian-vehicular interactions at crossings.

Table 2: Link and pedestrian crossing types

Link type	Pedestrian crossing type
Pedestrianised street	Not applicable
Shared space	Uncontrolled
Access road	Uncontrolled
Local distributor road	Zebra
District distributor road	Puffin / Pelican signal controlled
Primary distributor road	Grade separated

4.2.1 Pedestrian behaviour along links

Willis et al (2004) observe that 'remarkably little is known about how pedestrians actually negotiate urban spaces'. They analysed covertly-recorded video footage of pedestrians negotiating pavements along single-carriageway roads in York and Edinburgh, UK. 2613 pedestrians were recorded. The mean walking speed was

observed to be 1.47 m/s. Men (1.52 m/s) were shown to walk faster than women (1.42 m/s). Walking speeds declined with age (over 65s walked at 1.16 m/s compared to 1.47 m/s for those aged 26-50). Single pedestrians (1.52 m/s) walked faster than those in groups (1.36 m/s). Pedestrians were observed to walk more slowly in the middle of the day compared to the morning and evening commuting periods. Journey purpose, and hence 'time pressure' is therefore expected to affect walking speed.

With respect to spatial positioning, those walking in groups (22%) were more likely to walk in the road than single pedestrians (15%). Single pedestrians generally positioned themselves in the centre of the pavement suggesting that they prefer to maintain an equal amount of space on either side, rather than avoiding proximity to traffic. There were indications that having more space available was associated with higher walking speeds.

4.2.2 The effect of traffic on pedestrians

Hine and Russell (1996) investigate the 'barrier' effects of traffic on pedestrians. The traffic barrier is defined as: "the sum of inhibiting effects upon pedestrian behaviour resulting from the impact of traffic conditions: including physical (observable) and psychological (unobservable) impediments to pedestrian movement" (this is a development of the definition of severance provided in "Roads and Traffic in Urban Areas" (Department of Transport 1987)). It follows from this that the barrier effect of traffic cannot simply be measured through observation of pedestrian behaviour as no attempts to cross will be made if the pedestrian 'feels' unsafe.

A study is performed of the traffic barrier effects on pedestrians along two routes in Edinburgh, UK. The case study locations were mixed use streets with relatively high traffic flows (12 hour flows of 15,700 vehicles). This created conditions along which "major pedestrian / vehicular conflicts arise". Pedestrian and traffic conditions were video recorded. The video analysis was followed up with an on-street questionnaire survey and a number of in-depth interviews to examine pedestrian perceptions.

Crossing delay was found to be weakly correlated with traffic volume, and more strongly related to nearside than farside traffic volumes. Traffic speed (which is a function of traffic volume) was found to be less important to crossing delay. The young and elderly pedestrians experienced longer crossing delays and lower crossing ratios (number of pedestrians crossing divided by pedestrian flow) than other age groups. Longer crossing delays were also associated with steeper (straight across) crossing angles. Pedestrians accepted shorter gaps in heavier traffic conditions. 62 per cent of pedestrians were observed to cross from behind parked cars at one of the case study sites. This was found to be associated with steeper crossing angles, suggesting limited ability to choose the crossing route when faced with parked cars. Children and the elderly were found to be more inclined to use formal Pelican crossings than other age groups. Hence, overall, the barrier effect of traffic was shown to be amplified for children and the elderly relative to other age groups. The follow-up survey revealed that respondents were more inclined to choose a formal crossing in heavy traffic conditions, but when traffic slowed due to congestion, pedestrians were more inclined to cross informally.

Calvert (2015) conducted in-depth qualitative interviews with 31 pedestrians from Bristol, UK. 11 of these discussions were walk-along interviews with road conditions being discussed whilst walking in a city centre. Calvert collected empirical evidence supporting Taylor's (2003) contention that motor traffic can have substantial negative impacts on pedestrian experience. However, these impacts were found to be very variable, according to the pedestrian. Some were strongly and adversely effected by the proximity of traffic but others were untroubled by it. Calvert proposes that a number of mitigating factors may lessen the effects for the latter group. These include a perception that car use (often related to 'my car use') is necessary, apathy about the prospects of being able to reduce car use, empathy directed towards drivers and various types of barriers. Calvert suggests that motorised streets can be thought of as barriered spaces in a number of different respects: Barriers of various kinds, most obviously the pavement, can mitigate the negative effects of motor traffic's presence for the pedestrian, but can also impose a sense of restriction. The efficacy of barriers against the negative influence of traffic were very variable by participant. Traffic itself can also form a barrier, squeezing and marginalising pedestrians into narrow spaces. Thus a number of pedestrians

expressed relief and enjoyment at entering pedestrianised streets where these various barrier effects from traffic were lessened.

Calvert's participants did not overall report frustration at waiting to cross roads. What rare frustration was expressed was aimed at local councils rather than motorists. Predictably, older participants expressed some apprehension at crossing in time. One older participant related planning her walking route according to the placement of helpful crossing points. However, the pedestrians interviewed did not relate forgoing journeys, or significantly altering routes, due to barrier effects impeding crossing roads.

4.2.3 Interactions with vehicles in 'Shared Spaces'

As outlined in section 4.1.2, in traditional street designs, pedestrians are segregated from and hence do not physically interact with vehicles (though there is a psychological impediment). 'Shared Spaces', where pedestrians and vehicles have equal priority over road space, are an exception. These provide a context in which it is possible to examine how pedestrians and motorists negotiate right of way under different conditions.

Perceptions of drivers and pedestrians towards space sharing

Kaparias et al (2012) examine the differing perceptions of drivers and pedestrians towards shared space using a stated-preference design. A web based survey was completed by 871 pedestrians and 298 drivers. Pedestrian respondents were asked "Would you be comfortable moving around this space if it had the following combination of characteristics?" Drivers were asked "Would you be willing to drive on the below surface and share the space with pedestrians and cyclists?" Respondents were asked to evaluate this for a selection of 16 shared space scenarios (constructed based on seven attributes).

Pedestrians were found to prefer environments with low levels of vehicular traffic, high levels of pedestrian traffic, good lighting and pedestrian only facilities. Men and people aged less than 30 reported being more comfortable in shared spaces. Drivers were found to be less willing to share space as pedestrian numbers increased (particularly the numbers of elderly people and children), but prior knowledge increased willingness to share space. Male drivers reported greater willingness to share spaces than female drivers.

Prevalence of conflicts in Shared Spaces

Kaparias et al (2013) developed a 'pedestrian-vehicle conflict analysis method' and applied this to examine the number of conflicts occurring between pedestrians and vehicles along the Exhibition Road shared-space site in London, UK. The US Federal Highway Administration define conflicts as events "involving two or more road users, in which the action of one user causes the other user to make an evasive manoeuvre to avoid a collision". Kaparias et al (2013) classify conflict severity through consideration of: 1) Time to collision (between approaching road users and the projected collision point); 2) Severity of evasive action (i.e. how much users needed to decelerate); 3) Complexity of evasive action (categorised as 'simple' – deceleration only, or 'complex' – deceleration plus change of course) and 4) Distance to collision (between approaching road users and the projected collision point). Video data is used to assess the number of conflicts occurring before and after the conversion of Exhibition Road to shared space. The number of conflicts is shown to decrease after conversion, but it is also observed that pedestrian numbers increased, while vehicle numbers reduced.

Pedestrian - driver behaviour in shared space

Moody and Melia (2012) conducted an observational study of pedestrian behaviour in the Elwick Square shared space scheme in Ashford, Kent (UK). This scheme involved converting a one way inner ring road (traditional segregated design) into a two way, 20mph fully shared space environment. The square design also included marked 'courtesy crossings' around its periphery (where traditional crossings would ordinarily be positioned). Traffic volumes were of the order of 11,000 movements per day, which is high for a shared space scheme.

Video observations were used to record 179 crossing movements. 56% of the crossing movements involved moving around the periphery of the scheme, indicating that over half of those crossing sought to avoid conflicts with vehicles rather than following the most direct path. When conflicts between pedestrians and vehicles occurred, pedestrians tended to initially give way to the vehicle (in 72% of cases, though in 20% of cases, vehicles later gave way to pedestrians). The courtesy crossings were not treated as zebra crossings by drivers (who did not give way in the majority of cases). In follow up interviews (n=144), 72% of respondents stated that they 'worried about sharing space in Elwick Square'. 78% of respondents felt that they had less priority over vehicles compared to the previous street design. 64% stated that they would prefer traditional pavements and traffic light crossings. Men were found to hold more positive views than women.

An interesting question here is: **how do AVs affect perceptions of shared space amongst different road users?**

4.2.4 Summary

Walking speeds along links are found to be related to gender, age, journey purpose and pedestrian group size. There is little *physical* interaction between pedestrians and vehicles along links, since traditional street designs segregate pedestrians from vehicles. However, there is a *barrier effect* of traffic which relates to both physical and psychological impediments to pedestrian movements. Traffic barrier effects are more significant for children and the elderly.

Shared space schemes are preferred by pedestrians in low volume, low speed traffic environments. Pedestrians have shown a tendency to yield to motorists in heavily trafficked shared space schemes (based on a single UK case study).

The relevant research questions so far as AVs are concerned are: **Will the 'barrier effects' of mixed traffic streams to pedestrians be increased or reduced by the presence of AVs? Will pedestrians feel more or less able to gain priority over AVs (compared to driven vehicles) in Shared Spaces?**

4.3 Pedestrian-vehicle interactions at crossings

The report now reviews evidence in turn, of the behaviour of pedestrians at i) uncontrolled crossings, ii) designated (but un-signalised) crossings (including zebras) and iii) signalised crossings.

4.3.1 General crossing behaviour and uncontrolled crossings

At uncontrolled crossings, the cognitive burden on pedestrians and the potential for interaction with vehicles is heightened. Note that this section of the review includes observations on general pedestrian crossing behaviour such as gap acceptance and crossing speed, some of which emerged from studies of multiple crossing types.

Communications strategies

There seems to be surprisingly little research on the different communication strategies employed by drivers and pedestrians to negotiate conflict points, in the absence of traffic engineering control. Sucha (2014) conducted focus groups with pedestrians and drivers to examine their experiences of pedestrian crossings, perceptions of other road users and different means of communication. Pedestrians explained that they use eye-contact and hand signals to anticipate when it is safe to cross. Thank you signals are also employed (hand waving, nodding, smiling). Drivers reported using similar communication techniques, but also explained employing strategies such as not slowing down and maintaining a central road position to avoid having to stop for pedestrians.

The relevant research question so far as AVs is concerned is related: **how will AV sensing be able to detect and react to signals that pedestrians are gesturing and how will these be interpreted by the AV in its decision making?**

Walking speeds at crossings

Ishaque and Noland (2008) conduct a review of 'behavioural issues in pedestrian speed choice and street crossing behaviour'. The review concentrates on factors associated with pedestrian speed and the extent to which pedestrians 'comply with street crossing regulations'.

UK studies identified mean walking speeds at various crossing types of between 1.32 and 1.57 m/s for 'younger' adults. Elderly pedestrians have been observed to cross roads at lower speeds of between 1.11 and 1.16 m/s (on average) (Cresswell *et al.*, 1978; Wilson and Grayson, 1980; Griffiths *et al.*, 1984). In an older Swedish study (Sjostedt 1967, quoted by Sleight, 1972), children were observed to have the fastest crossing speeds. This was attributed to children being more likely to run across roads compared to other age groups. At signalised crossings, Gates *et al* (2005) confirmed that pedestrian crossing speeds increased outside of the pedestrian green phase (from 1.37 m/s to 1.52 m/s).

Crompton (1979) observed that crossing speed increases with delay at the kerbside, particularly when the delay increases beyond 15 seconds. This could be due to a desire to make up for lost time, or alternatively be related to higher traffic volumes, which necessitates faster crossing. Zebra crossings were shown to produce the lowest delay to pedestrians and the lowest crossing speed.

An interesting research question is therefore: **Will AVs be able to detect different types of pedestrian (e.g. children and older people) in the environment and be primed to respond to potential crossing interactions accordingly.**

Gap acceptance at crossings

An early UK (Manchester) study by Cohen *et al* (1955) (cited in Ishaque and Noland (2008)) found that every pedestrian (negotiating a 7m wide crossing) accepted gaps between approaching vehicles of 10.5 seconds or more, but no one accepted gaps of less than 1.5 seconds. 92% of pedestrians crossed the road where gaps were seven seconds or more. Das *et al* (2005) observed (in an Indian study) that pedestrians waiting on central refuges accepted shorter gaps than those waiting on the curb side. This is also observed in Hamed (2001).

Brewer *et al* (2006) report on a US study which examined gap acceptance at unsignalised crossings. Observational data on 42 crossing sites was analysed. In high traffic volume contexts, pedestrians were observed to seek 'rolling gaps' – where pedestrians do not wait for all lanes to clear, but instead anticipate where a gap will be available in the next lane. The 85th percentile for accepted gaps was found to lie between 5.0 seconds and 9.4 seconds.

An interesting research question is: **will pedestrians adjust the gap that they are prepared to accept to make a crossing of a road when the next approaching vehicle is demonstrably an AV rather than a human-driven vehicle?**

Compliance with crossing regulations

Non-compliance with regulations (e.g. avoiding designated crossings, or crossing on red signals) has been shown to be associated with carriageway width (and hence the risk profile of the crossing). People are more likely to take risks at narrower crossing points (e.g. Eustace 2001 (cited in Ishaque and Noland (2008), based on a study in Kansas, USA). It should be noted however, that non-compliance is not illegal in the UK. Increased waiting times at the kerbside have also been shown to be associated with non-compliance in North America. In a Canadian study by Baas (cited in Walker *et al* 2005), a waiting time of 40 seconds was identified as a threshold after which pedestrian non-compliance increases significantly.

Choosing where to cross

Sisiopiku *et al* (2003) analysed pedestrian crossing behaviour (using video recordings) at different crossing types located along a 1-km long boulevard in East Lansing in Michigan, USA. This analysis was followed up with a survey to examine perceptions of the crossing environment amongst 711 users of the street (students of a nearby university). 90 per cent of survey respondents explained that the distance to the crossing point was the main determinant of where they chose to cross. 83% of respondents noted that the availability of a 'midblock crosswalk' (a central refuge) influenced whether they crossed at a particular location or not. 61% of respondents agreed that motorists should only yield to pedestrians at designated cross-walks, though a

significant minority, 31 per cent, felt that motorists should always yield to pedestrians. With respect to pedestrian behaviour at signalised junctions, 90% of respondents stated that they would cross given an acceptable gap, or when traffic had cleared, rather than waiting for the green signal. Motorists turning into side streets were observed to generally fail to give way to pedestrians crossing the side street, even though pedestrians had priority during pedestrian green phases (which were shared with vehicles).

Socio-demographic and social-psychological relationships

Holland and Hill (2007) examined “the effect of age gender and driver status on pedestrians’ intentions to cross the road in risky situations”, applying the Theory of Planned Behaviour (TPB). They conduct a stated preference survey with 293 participants. The survey asked respondents to evaluate their intention to cross the road under three scenarios: Scenario A: Crossing a shopping street at an uncontrolled location in place of walking to a nearby crossing point; Scenario B: Crossing a busy dual carriageway by gap accepting; and Scenario C: Crossing on a bend where it appears there is no traffic (though visibility is poor).

Avoiding using a designated crossing along a shopping street was perceived to be the least risky situation. Intention to cross was shown to decline with age (older people were risk averse), but gender or driver status had no effect. In relation to constructs from the TPB, men and drivers were found to hold more positive attitudes towards crossing than women and non-drivers. Subjective norms (whether one believes others think you ought not to cross in different contexts) were found to more strongly predict the intentions of younger people, than the intentions of older people. The authors interpret their findings as suggesting that there are different decision making processes at play for different population groups (younger vs older pedestrians, driving vs non-driving pedestrians).

Evans and Norman (1998) conducted a similar stated preference survey (n=210) to examine the extent to which social-psychological constructs from the TPB predict intentions to cross roads in three potentially hazardous situations: gap accepting at a dual carriageway; crossing on the red man at a pelican crossing (in the presence of two other pedestrians) and crossing between parked cars along a residential street (instead of using a zebra crossing). The survey was conducted in West Glamorgan, Wales. Perceived behavioural control (how easy it is perceived to cross the road) was found to be the strongest predictor of intention to cross the road. Hence the authors suggest that crossing treatments ought to influence pedestrians’ perceptions in improving safety at dangerous crossing points (making it look difficult to cross for example). Older people had lower intentions to cross the road than younger people. Perceived behavioural control was also found to be weakly correlated with perceptions of risk. Subjective norms were observed to be more important when other pedestrians were present (Scenario B). This indicates that people will consider how other pedestrians are behaving when making decision concerning whether to cross. Self-identity was also important with those identifying themselves as ‘safe pedestrians’ being less likely to report risky crossing behaviour.

de Lavalette et al (2009) “propose that crossing behaviour is determined partly by the task to be accomplished [crossing the road] and partly by the physical environment in which the crossing takes place”. Crossing the road is contextualised as being secondary to the “journey itself”, the purpose of which may alter crossing behaviour. They observe 4000 pedestrians crossing 12 junctions located in Montreal, Canada. The junctions were classified according to presence of pedestrian signals, number of traffic lanes, one or two way traffic. The paper presents an early analysis of the data which is not yet complete. They find that pedestrians are more likely to violate crossing regulations (crossing before signals allow) if there is no specific crossing signal for pedestrians, or if there is a central refuge (which reduces the traffic surveying burden on the pedestrians). They suggest that that “the environment has to be interpreted, notably in terms of its topographical features (e.g. number of lanes of traffic to cross), its infrastructure (e.g. presence of a central traffic island), its control systems (e.g. traffic signals for vehicles and pedestrians), but also within the context of the pedestrian’s primary task (getting to school, going shopping, etc.)”.

Hamed (2001) observed the crossing behaviour of 400 pedestrians in Amman, Jordan (350 of which were later interviewed). It is not clear how the crossings are controlled (although it appears they are not signalised and pedestrians gap accepted or waited for a motorists to yield). Crossing and waiting times and the number of attempts required to cross were recorded, as were traffic volumes, speeds and headways. The survey was conducted in September 1998.

Frequency of use of a particular crossing point (increasing familiarity) was observed to be associated with higher risk taking and lower waiting time, as was being on the way to work. Lower risk taking was associated with having been involved in a traffic collision, owning a private vehicle (indicating that drivers are more aware of crossing risk), being female, crossing with children, and being older. Waiting times were shown to reduce as the number of pedestrians increased, indicating that a larger pedestrian presence can increase 'right of way'. Pedestrians made more attempts to cross the road in heavy traffic and were observed to be sensitive to the type of approaching vehicle – the number of attempts to cross reduced if the approaching vehicle were a large bus (potentially in relation to lower approach speeds). On divided streets (with a central refuge), a longer waiting time at the first curb was found to be associated with greater risk taking in crossing from the central refuge – Pedestrians become impatient to cross.

The relevant research questions so far as AVs are concerned are: **will pedestrians' intention to cross change as the approaching vehicle is demonstrably an AV? Will this intention to cross vary according to demographic (age, gender) or situational characteristics (traffic volume, road type, prior experience of AVs)?**

4.3.2 Unsignalised designated (including zebra) crossings

Varhelyi (1998) examines "drivers' speed behaviour at a zebra crossing" in Lund, Sweden. He concludes from a review of international literature on behaviour at zebra crossings that: i. drivers give way to pedestrians in less than half of all encounters (between 4% and 30%); ii. drivers do not tend to adapt the speed sufficiently on approaches to zebras and that the presence of pedestrians at the kerbside does little to alter driver behaviour and iii. drivers are more willing to stop if they are already travelling slowly. He conducted his own observational study of driver behaviour on the approach to a zebra crossing along a two lane arterial road in Lund, Sweden. Pedestrians are found to gain priority in only 5% of interactions at the zebra crossing (of 790 observed encounters). He suggests that drivers "do not adapt the speed in such a way that they do not endanger pedestrians who are already on, or are about to step onto the zebra crossing". Indeed, three quarters of drivers were observed to maintain their speed or even accelerated as they approached the crossing. This is interpreted as a strategy used to maintain priority. He concludes that driver behaviour ought to be influenced prior to reaching a 'decision zone' which is identified as being 50m to 40m before the crossing.

The relevant research question so far as AVs are concerned is: **Are AVs programmable to effectively and automatically adapt their speed within zebra crossing 'decision zones' regardless of whether pedestrians are present?**

Turner et al (2006) conducted a study of motorist yielding behaviour at unsignalised intersections with designated pedestrian crossings in the USA. In the US, motorists are required to yield to pedestrians at marked crossings without signals. Data was collected at 42 crossing sites located across the country. All of the crossings were marked and involved one of three types of traffic management: 1. A red (stop) sign indicating presence of pedestrian crossing 2. Active devices that display a signal only when pedestrians are present 3. A treatment to increase the visibility of the crossing location. Video recordings were made during the daytime at the case study sites (in October and November 2003). Motorist yielding rates were calculated as the number of yielding motorists divided by the total number of motorists that ought to have yielded.

Red (stop or warning) signals were found to be highly effective, with yielding rates of 94%. These send a clear message to motorists. The active and treatment only crossings were less effective and generated a greater range of yielding responses (between 31% and 65% for active crossings and between 17% and 87% for treatments). This was attributed to greater variation in environmental conditions (E.g. traffic volumes, road widths). Indeed, for treatment crossings, the number of lanes crossed was found to be a significant predictor of motorist yielding rates. Flags, refuge islands and high visibility markings produced better compliance rates on lower speed roads (and this was statistically significant). It is concluded that the type of crossing does have an effect on motorist yielding behaviour.

The relevant research question so far as AVs are concerned is: **What is the extent to which AVs are programmable to effectively and consistently respond to different types of crossing treatment?**

A further type of uncontrolled crossing is the crossing of a side road connecting to a major road. Typically, a side road will bisect a footway and a pedestrian will have to cross the side road to proceed along the major road. This act of ‘crossing’ the side road, unlike the act of passing the side road if driving or cycling along the major road, creates a conflict between the pedestrian and any road user that is turning into, or turning out of, the side road. As Rule 8 of The Highway Code states, pedestrians have right of way across a side road if they have already begun to cross. This poses potentially interesting dilemmas depending on the relative speed of approach of the pedestrian and traffic within the carriageway.

A critically important question so far as AVs are concerned is as follows: **how good are AVs at detecting pedestrians approaching and crossing side roads and are they able to respond accordingly?** In a similar but related way, a further question is: **how do pedestrians react to a vehicle which is demonstrably autonomous when deciding whether to start to cross a side road?**

4.3.3 Signalised crossings

Signalised crossings aim to minimise conflicts between motorists and pedestrians, hence reducing the level of interaction between them.

Walker et al (2005) report on a comparison of pedestrian behaviour at Pelican and Puffin crossings. Puffin crossings replace a farside green man indicator with a nearside indicator (with the intention of focussing attention on oncoming traffic). Puffin type control uses on-crossing detection to vary the green time and uses waiting area detection to cancel demand if pedestrians move away after calling a pedestrian stage. The flashing amber - green man period used on Pelican crossings is also replaced with an extended red period for traffic (with a red signal also given to pedestrians). Puffin crossings are recommended by the UK Department for Transport for new installations and refurbishments of existing signal controlled crossings as opposed to the more traditional ‘Pelican’ type of control. Observations were taken at five Puffin sites which were paired with comparable Pelican sites.

No differences in the number of potential conflicts at Puffin and Pelican crossings were observed. Pedestrians were more likely to begin crossing on a flashing green man at Pelicans compared to the red extension period used at Puffins (1% of pedestrians at Pelicans compared to 0.1% of pedestrians at Puffins). This indicates that pedestrians react to positive signals to cross. Pedestrians were more likely to cross on red as waiting times increased.

Davies (1992) (cited in Sisiopiku et al 2003) conducted a study of pedestrian behaviour at the first round of ‘Puffin’ crossings installed in the UK. He found that over 50% of pedestrians chose to cross the road without pressing the push button to register their presence. The level of compliance was dependent on context e.g. Compliance was as low as 27% in London (a heavily trafficked urban environment) but was shown to be 49% in a small town.

Parkin and Wilson (2010) investigated in the UK, vehicle and pedestrian detection offered by ‘Puffin’ type control at signal controlled mid-block crossings. A survey of delays over fifty cycles caused to pedestrians and vehicles at three Puffin and three Pelican crossings (without pedestrian detection) with matched attributes was conducted. Pedestrian arrival times, time of demand request, pedestrian crossing times and vehicle delays were recorded. Observations were collected on pedestrians’ behaviour relating the time when they called for a pedestrian stage, the time of the invitation to cross and the time at which they actually crossed.

Analysis of the data showed that there is an increase in delay to pedestrians and vehicles at Puffin crossings when compared with equivalent Pelican crossings. The increase in vehicle delay results from the generally longer time to return to a green signal aspect for motor traffic after a pedestrian green aspect. The data show that this additional time is not required for pedestrians to clear the crossing. The suggestion is that the flashing amber period of a Pelican, which occurs after the green period for pedestrians, performs this function adequately. Even under the high vehicle flow conditions which obtained during the survey periods, significant non-compliance in pressing the button to create a demand was observed at Puffins (maximum 28%), and this was more than at Pelicans (maximum 23%). Observations also suggest that the tuning of pedestrian detection equipment remains a significant issue. No conflicts were observed during the Pelican flashing amber period, but five red light violations were observed in the red period after the pedestrian period at Puffin crossings.

4.3.4 Summary

Walking speeds at crossings have been shown to be related to age, with elderly people crossing more slowly and children crossing more quickly than other age groups. Walking speeds increase when crossing from the middle of the road, or on a flashing green man at Pelican crossings.

Most pedestrians accept gaps of 7 seconds or more. 'Rolling gaps' are sought when traffic volumes are high.

Being risk averse is associated with being older, being female, owning a vehicle, and being unfamiliar with the crossing location. Younger people are more concerned about subjective norms. Crossing decisions are influenced by those of other nearby pedestrians in group situations.

Driver yielding rates at unsignalised crossings are influenced by treatment type and the road environment. Red signs with clear instructions are most effective (in the USA). It has been shown that the majority of drivers avoid yielding at zebra crossings.

An interesting research question is: **what is the extent to which an AV will be able to detect the significant non-compliance with signal controlled crossings by pedestrians who have become frustrated with the delay imposed on them by the signalisation of crossings?**

A further interesting question which leads on from this is: **how will AVs respond to non-compliance (i.e. would an AV be required to defer to a pedestrian in its path in all situations when safe to do so, even on higher-speed roads)?**

4.4 Pedestrian Protection Systems

Gandhi and Trivedi (2007) reviewed research into 'pedestrian protection systems' i.e. the use of intelligent transport systems to reduce the probability of vehicle to pedestrian collisions. They note that injuries to pedestrians can be prevented or reduced in severity through infrastructure and vehicle design. Infrastructure design refers to measures such as speed control, traffic management to separate pedestrians and vehicles (particularly at crossings as reviewed in section 4.2) and measures to increase pedestrian visibility such as improved lighting and removal of on-street parking. Vehicle design affects injury severity. Pedestrian fatalities are usually the result of head injuries, generally caused by the head coming into contact with a hard surface such as the windshield. 'Active hoods' enable bonnets to automatically rise during collisions so that the head comes into contact with a deformable surface.

4.4.1 Intermediate technology

A further enhancement, which is currently under development, is the use of vehicle mounted *pedestrian detection systems*. These are designed to provide drivers with either advanced warning of the presence of pedestrians or assistive braking in circumstances in which a collision is predicted to be unavoidable. Vehicles are equipped with sensors (optical, infrared, laser or radar) to monitor the surrounding environment. The sensors are mounted around the vehicle in order to provide binocular vision and depth perception. Image processing algorithms are used to distinguish pedestrian 'objects' from other features. Tracking algorithms predict pedestrian movements and the likelihood of collision.

There are a number of technical challenges however. Visibility from vehicle mounted sensors is limited. The effective visibility of the vehicle can be enhanced through the use of road side infrastructure which monitors pedestrian movements and vehicle activity and broadcasts this to passing vehicles. This can be deployed in highly populated or at risk areas e.g. near schools or on unprotected left (UK right) turns. A similar effect (improving sensing of the distant environment) can be achieved through the use of vehicle to vehicle communication, though both forms of communication technology are expensive.

It is notable that Gandhi and Trivedi (2007) observe that technology struggles to compete with the human sensory system which is highly effective at detecting surroundings and making decisions in real time.

4.4.2 Designs for autonomous vehicles

Technology companies have already started designing systems to enable AVs to communicate with pedestrians. A patent filed by Google in November 2015 (United States Patent Office 2015) describes a

system in which electronic displays are installed on vehicle panels to present messages to pedestrians (images or text) such as 'safe to cross' or a stop sign. Speaker systems are incorporated in the design to enable audible messages to be broadcast. The patent includes an aspiration to develop 'mechanisms that mimic human behaviour such as a robotic hand to make gestures or robotic eyes on the vehicle that allow the pedestrian to recognize that the vehicle "sees" the pedestrian.

4.4.3 Moral dilemmas

Lastly, it is informative to briefly consider challenging moral questions concerning how AVs ought to be programmed to minimise injury and death in the event of an unavoidable collision. For example, Goldhill (2015) asks "should driverless cars kill their own passengers to save a pedestrian"? This moral dilemma is analogous to the 'Trolley Problem' thought experiment (see Box 1).

Box 1: The Trolley Problem

Scenario A

A runaway train is heading towards five railway workers.

You have the option of operating a switch to divert the train onto a spur. There is only one railway employee working on the spur.

Not operating the switch will mean that the train kills five workers.

Operating the switch will divert the train, but kill one worker.

Most people suggest that the switch should be operated to minimise the loss of life.

Scenario B

A runaway train is heading towards five railway workers.

In this case, there is no way of diverting the train.

But you have the option of pushing a large man onto the track.

This will kill the large man, but will save the five railway workers.

Most people suggest that pushing the man into the track is the wrong course of action, even though it leads to the same outcome as scenario A (minimising loss of life).

<https://www.youtube.com/watch?v=bOpf6KcWYyw>

The different responses to the two scenarios arise from the trade-off between a desire to minimise loss of life on the one hand and to not directly cause harm to another human being on the other. Proponents of 'utilitarianism' argue that the correct course of action is always the one that 'maximises happiness', in this case minimising the loss of life. This rational approach suggests that AVs should always be programmed to limit the number of fatalities, even if this means killing a pedestrian. However, philosophers have argued that it is necessary to also consider who is morally responsible for the loss of life. For instance, if the AV contains only adults that ought to be aware of the risks when entering the vehicle, then the AV should not be programmed to kill any number of pedestrians in order to save the lives of its passengers. This situation becomes less justifiable as the number of child passengers in the AV increases. Bonnefon et al. (2015) conducted an online survey (n=201) to examine lay views on this topic. 75 per cent of respondents agreed that an AV should swerve into a barrier (killing its sole passenger) to save 10 pedestrians.

Hence an area that demands further research is as follows: **how does the general population think AVs ought to be programmed to take action in the event of unavoidable collisions involving pedestrians?**

5 Conclusions and research questions

The review has covered literature pertaining directly to Autonomous Vehicles, to interactions between motor vehicles and the principal other forms of traffic found on urban roads, namely cycle users and pedestrians, and interactions between vehicles and infrastructure. It has included literature from around the world where driving behaviour and the nature of the infrastructure may be different from the UK situation.

This wide-ranging purview was deliberate in order to develop as many of the appropriate research questions as possible that are relevant to the introduction of autonomous vehicles in mixed conditions in the urban environment. As a framework, we defined four Use Scenarios as follows to help understand the context of

possible AV use: 1) Fully segregated AV network, 2) Motorway or expressway network, 3) Typical Urban network, 4) Shared space. The focus of the research will however, be in relation to Use Scenarios 3 and 4. The table below summarises the research questions that have emanated from the literature review and each has been assessed in terms of the ability of the Venturer trial to provide an answer to the question. It is envisaged that only the seventeen question that have been rated as having a high ability to be answered by the trial will be given further consideration in the development of the interaction trials.

Section	Research Question	Ability to answer	Comment
2.2	What decision making behaviour may be required of an AV to deal with aggressive behaviour of a human driver in a following vehicle?	Low	Difficult to establish and measure responses in free-flowing traffic.
2.3.1	As a result of their greater predictability, will the presence of autonomous vehicles introduce a degree of additional control into the vehicle mix, resulting in fewer errors by drivers?	Low	Only one AV is being used in the trials.
2.3.1	Do approaching AVs, when they are clearly distinguishable as such, engender a different gap acceptance behaviour amongst other road users, at priority junctions?	High	The issue of gap acceptance is a central issue in priority junction control.
2.3.2	Do approaching AVs, when they are clearly distinguishable as such, engender a different gap acceptance behaviour amongst other road users, at roundabouts?	High	Despite being a relevant and highly possible condition to test, it is likely that the majority of the information on gap acceptance may be derived from behaviour at priority junctions, as above.
2.3.3	Do approaching AVs, when they are clearly distinguishable as such, engender a different gap acceptance behaviour amongst other road users, at merges?	Low	This scenario would require testing on high speed roads and is outside the scope of the trials.
2.3.5	How will AVs behave in shared space? (See also research question from section 4.2.3)	High	While Shared Space is currently limited in extent, it is likely to become more prevalent. Rudimentary shared space is relatively easy scenario to create.

2.5.1	How for example might an AV manage a situation in which another driver is being deliberately antagonistic, driving in a manner with the intention to harm the AV and/or its occupants, or simply driving with poor care and attention to the task of driving?	Low	It would be difficult to create such a situation in a trial.
3.2	Will AVs assist, in the generality, in changing the perceptions of hazard posed by motorised traffic to cycle users?	Low	This question is only able to be answered in the long term
3.3.1	How does the presence of AVs with differing levels of automation affect interactions and decisions made by cyclists?	Low	This is an important question but it is difficult to answer in the context of the Venturer trial.
3.3.1	How will the evolution of machine learning and related human learning take place while maintaining safe interactions between vehicles and cyclists?	Low	Again, this is an important, but a question that may be answered only in the longer term.
3.3.2	To what extent would AVs be able to detect a cyclist in the road ahead when light and weather conditions are adverse?	Medium	This is an important question, but would be possible, but difficult to engineer in the context of the Venturer trials.
3.3.2	What is the extent to which an AV, when not being driven, can remain what might be termed 'passively' safe by preventing passenger egress when it is not safe for the occupants or others in the vicinity, such as cyclists to do so?	High	This ought be technologically easy to specify and can be readily tested.
3.4.1	How may perceived risk within a network be altered for cycle users by the presence of AVs in the vehicle stream?	Low	Not possible in the context of the Venturer trials
3.4.2	Are AVs able to overtake cyclists both with and without centre line markings with no difference in the impact on cycle users perceptions of safety?	High	Responses to overtaking behaviour in a variety of circumstances is important to estimate.
3.4.2	For different speeds, what is an appropriate distance to be provided by an AV when overtaking a cyclist in order to provide a minimum level of comfort for the cyclist?	High	AVs could have a significant beneficial impact within the road environment if they reduce the perceptions of danger linked with overtaking.

3.4.3	How will cycle users negotiate road narrowings with AVs without the facility to use eye contact as part of negotiating the manoeuvre?	High	Road narrowings are a regular feature of the road network and cause significant issues in relation to overtaking and general driver behaviour.
3.4.4	How accurate are AVs in detecting cyclists who are making straight on manoeuvres at junctions across side roads either within the carriageway or on adjacent cycle tracks and what is the ability of the AV to come to a correct decision about its behaviour in relation to the cyclist or cyclists?	High	This is a key question that the trials need to answer
3.4.5	Will AVs be regarded any differently by cycle users in terms of where they allocate attention as they approach an AV in a queue with the intention of overtaking it, and will cyclists make different decisions about whether to overtake the AV or undertake it, and what will be cyclists perceptions of risk when they approach an AV when it is in a queue?	Medium	These questions relate to important aspects of the perception of AVs, however, they are, relatively speaking, secondary in nature relative to other issues such as gap acceptance.
3.4.6	What is the extent to which AVs are able to decipher cyclists arm signals accurately at junctions?	High	It is important to understand the ability of an AV to interpret human gestures
3.4.7	What legislative changes might be particularly appropriate or helpful in the context of managing AV interactions with other road users?	Medium	This question may be answerable as a consequence of the overall research and not necessarily emanating from the trials of interactions per se.
3.5	What roles will cyclists and pedestrians have in a driverless society and how will the presence of driverless vehicles change pedestrians' and cyclists' facility preferences and behaviour?	High	Not possible in the trials but some suggestions feasible from wider public engagement
4.1.7	How ought the Highway Code to be adapted to provide guidance to pedestrians (and other road users) on how to negotiate right of way with autonomous vehicles?	Low	The research will present some ideas which will be helpful in moving towards an answer to this question

4.2.3	How do AVs affect perceptions of shared space amongst different road users? (See also research question from section 2.3.4)	Medium	User perception of AV behaviour in shared space is an important area for research and we will be able to address this question to some extent through public engagement activity.
4.2.4	Will the 'barrier effects' of mixed traffic streams to pedestrians be increased or reduced by the presence of AVs?	Low	The Venturer trial will be using only one AV and hence will not be able to address this issue.
4.2.4	Will pedestrians feel more or less able to gain priority over AVs (compared to driven vehicles) in Shared Spaces?	Low	The Venturer trial will be using only one AV and hence will not be able to address this issue.
4.3.1	How will AV sensing be able to detect and react to signals that pedestrians are gesturing and how will these be interpreted by the AV in its decision making?	High	Understanding how AVs relate to pedestrians in the urban environment is critical to their success in this type of environment.
4.3.1	Will AVs be able to detect different types of pedestrian (e.g. children and older people) in the environment and be primed to respond to potential crossing interactions accordingly.	Low	It is assumed that the technology is not sufficiently advanced to be able to detect these differences currently.
4.3.1	Will pedestrians adjust the gap that they are prepared to accept to make a crossing of a road when the next approaching vehicle is demonstrably an AV rather than a human-driven vehicle?	High	Understanding pedestrian gap acceptance differences with AVs is important
4.3.1	Will pedestrians' intention to cross change as the approaching vehicle is demonstrably an AV?	High	This is an important issue that is possible to assess as part of the Venturer study
4.3.1	Will this intention to cross vary according to demographic (age, gender) or situational characteristics (traffic volume, road type, prior experience of AVs)?	Medium	It will be harder to assess this issue because of the degree of variability in the variables.
4.3.2	Are AVs programmable to effectively and automatically adapt their speed within zebra crossing 'decision zones' regardless of whether pedestrians are present?	High	It would be feasible to test for the effect of such differential programming on pedestrian behaviour

4.3.2	What is the extent to which AVs are programmable to effectively and consistently respond to different types of crossing treatment?	Medium	The variability in circumstances is difficult to test within the context of the proposed trials
4.3.2	How good are AVs at detecting pedestrians approaching and crossing side roads and are they able to respond accordingly?	High	This is a very common conflict and easily able to be tested in the trials
4.3.2	How do pedestrians react to a vehicle which is demonstrably autonomous when deciding whether to start to cross a side road?	High	This is a very common conflict and easily able to be tested in the trials
4.3.4	What is the extent to which an AV will be able to detect the significant non-compliance with signal controlled crossings by pedestrians who have become frustrated with the delay imposed on them by the signalisation of crossings?	Low	It will be a difficult task to create the right conditions to test this question
4.3.4	How will AVs respond to non-compliance (i.e. would an AV be required to defer to a pedestrian in its path in all situations when safe to do so, even on higher-speed roads)?	Low	It will be a difficult task to create the right conditions to test this question
4.4.3	How does the general population think AVs ought to be programmed to take action in the event of unavoidable collisions involving pedestrians?	High	This is a very important question and one that we may begin to seek answers to through the public engagement activities.

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Appendix A: Extracts from the UK Highway Code for Pedestrians

Rule 1:

Pavements (including any path along the side of a road) should be used if provided. Where possible, avoid being next to the kerb with your back to the traffic. If you have to step into the road, look both ways first. Always show due care and consideration for others.

Rule 2:

If there is no pavement, keep to the right-hand side of the road so that you can see oncoming traffic.

Rule 4:

Young children should not be out alone on the pavement or road (see Rule 7). When taking children out, keep between them and the traffic and hold their hands firmly. Strap very young children into push-chairs or use reins."

Crossing the road

Rule 7:

First find a safe place to cross and where there is space to reach the pavement on the other side. Where there is a crossing nearby, use it. It is safer to cross using a subway, a footbridge, an island, a zebra, pelican, toucan or puffin crossing, or where there is a crossing point controlled by a police officer, a school crossing patrol or a traffic warden. Otherwise choose a place where you can see clearly in all directions. Try to avoid crossing between parked cars (see Rule 14), on a blind bend, or close to the brow of a hill. Move to a space where drivers and riders can see you clearly. Do not cross the road diagonally.

Rule 8

At a junction. When crossing the road, look out for traffic turning into the road, especially from behind you. If you have started crossing and traffic wants to turn into the road, you have priority and they should give way

Rule 9

Pedestrian Safety Barriers. Where there are barriers, cross the road only at the gaps provided for pedestrians. Do not climb over the barriers or walk between them and the road.

Using crossings

Rule 18

At all crossings. When using any type of crossing you should

always check that the traffic has stopped before you start to cross or push a pram onto a crossing

always cross between the studs or over the zebra markings. Do not cross at the side of the crossing or on the zig-zag lines, as it can be dangerous.

You MUST NOT loiter on any type of crossing. – This is a law

Rule 19:

Zebra crossings. Give traffic plenty of time to see you and to stop before you start to cross. Vehicles will need more time when the road is slippery. Wait until traffic has stopped from both directions or the road is clear before crossing. Remember that traffic does not have to stop until someone has moved onto the crossing. Keep looking both ways, and listening, in case a driver or rider has not seen you and attempts to overtake a vehicle that has stopped.

Rule 21

At traffic lights. There may be special signals for pedestrians. You should only start to cross the road when the green figure shows. If you have started to cross the road and the green figure goes out, you should still have time to reach the other side, but do not delay. If no pedestrian signals have been provided, watch

carefully and do not cross until the traffic lights are red and the traffic has stopped. Keep looking and check for traffic that may be turning the corner. Remember that traffic lights may let traffic move in some lanes while traffic in other lanes has stopped.

Rule 191:

Rules for using the road:

Crossings

You **MUST NOT** park on a crossing or in the area covered by the zig-zag lines. You **MUST NOT** overtake the moving vehicle nearest the crossing or the vehicle nearest the crossing which has stopped to give way to pedestrians.

Rule 195

Zebra crossings. As you approach a zebra crossing

- look out for pedestrians waiting to cross and be ready to slow down or stop to let them cross
- you **MUST** give way when a pedestrian has moved onto a crossing
- allow more time for stopping on wet or icy roads
- do not wave or use your horn to invite pedestrians across; this could be dangerous if another vehicle is approaching
- be aware of pedestrians approaching from the side of the crossing.